SNOWFALL EVENT CHARACTERISTICS FROM A HIGH-ELEVATION SITE IN THE SOUTHERN APPALACHIAN MOUNTAINS

A Thesis
by
DANIEL TIMOTHY MARTIN

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Abstract

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Accurate assessment of snowfall patterns in high elevation remote areas is essential to providing the necessary boundary conditions for climatological analyses. The Southern Appalachian Mountain (SAM) region of the eastern U.S. provides a unique study area due to its low latitude and proximity to the Gulf of Mexico and Atlantic Ocean. Major snowstorms, such as Hurricane Sandy in October 2012, can result in heavy snowfall of 100 cm or greater in favored upslope regions. These characteristics make the understanding of precipitation patterns especially important as deep snowpack is often exposed to heavy rainfall, cloud immersion, and high dew point temperatures, further exacerbating flooding threats. To contribute to this understanding, the MObile Precipitation Research And Monitoring (MOPRAM) station was deployed at Roan Mountain (1875 m asl.) on the Tennessee/North Carolina border in October 2012. MOPRAM has allowed for the analysis of high-elevation variables such as temperature, liquid precipitation, and snow depth at high temporal resolutions during the 2012-13 snow season. In this paper, observed snowfall event characteristics are analyzed and compared with those of other sites in the SAM. The 25 snow events were characterized by conditionally unstable upstream lapse rates, northwest winds, high-to-low elevation precipitation enhancement near a factor of three, and 364 mm of seasonal snow liquid equivalent on Roan Mountain. About 391 cm of snow fell at Roan during the 2012-2013 season when using nearby snow liquid ratios as estimators.

Acknowledgments

The production of a thesis is in no way a trivial task; as a consequence, it is often the case that more than one individual is highly involved in the process of its production. While a single name appears for authorship on the Graduate School records, many others have worked directly or indirectly to guide that single name to success, whether it was academically, financially, or socially.

The highest order of gratitude is submitted to my parents: Charles and Suzanne Martin. From a very young age, they afforded me an opportunity that would have been doubtful had I remained in my native and orphaned state in east Romania. For as long as I can remember, my constant desire to understand the world around me was always granted by their support, be it through taking me to bizarre and exotic countries or simply buying that latest video game. They have also, of course, been a gracious vessel of financial support throughout my undergraduate and graduate academic careers, a support all but obligatory in a society that sometimes seems to deny the financial recognition that many hardworking scholars deserve. Wherever I may go next, it can be said with high confidence that they will offer support. I thank you both.

My academic development is the product of many years and unsung heroes offering years of hard work to bring myself and others where I am today. Most relevant to this production, however, remains my thesis committee, a group of individuals—friends that I regard not simply in the obligatory sense, but because they have offered so much dedication and sacrifice to ensure that this manuscript and my future career remain successful.

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Dedication

To

My Birth Parents, wherever they may be,

to

Little Miyah and all the other children, do not let your journey into adulthood jade your current sense of wonder. Always question, and always appreciate the complexity of the universe,

and to

My future life partner and friend, may we find each other with haste to maximize time spent "'til death do us part."

In memory of grandmother and fellow winter lover Virginia Irene Nelson (11 Dec 1919-04 July 2013)

"May the snow forever fall as you watch in peaceful rest."

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Foreword

The organization and formatting of the thesis main body strictly follows the instruction to authors for manuscript submission to the *Climate Research*, an official journal of the Inter-Research Science center.

Introduction and Motivation

Importance of Mountains

Assessing meteorological and climatological patterns of mountainous terrain is a difficult challenge for the research community. Sparse observations and complex terrain generally combine to result in gradients of atmospheric parameters (e.g., temperature, precipitation) that are difficult to both forecast and verify. Despite this complexity, it is important to understand these patterns as the livelihoods of many individuals depend on mountainous environments. Mountains consist of approximately a quarter of the Earth's land surface, while about thirteen percent of the global population resides above 2,500 m (Huddleston & Ataman 2003). Mountains also act as vital water supply to downstream communities, especially those in arid regions where precipitation and melting runoff are the primary source of water (Singh et al. 2011). This influence and dependence has resulted in idolization of terrain by many cultures (Bernbaum 1998). Complexity in terrain and proximity to rivers by many of the communities can be hazardous, however, as rapid discharge can occur with intense precipitation events (Hunter & Boyd 1999).

Since the mid-18th century, significant advancement has been made in the study of mountain weather and climate (de Saussure 1796). Delineations of "mountains" have had their history of ambiguity throughout scholarly history (Messerli & Ives 1997), with multiple definitions based on altitude and prominence (Thompson 1964) or latitudinal variation and climate (Troll 1973) being proposed. The first alpine instrumentation suite to systematically observe meteorological variables was placed in the Canary Islands during the 1850s (Smyth 1859). Despite a growing number of instrumentation stations, the challenges of observing weather and climate in mountains remain due to factors such as test beds being far from population centers and the inhospitable nature of many maintenance environments (Barry 2008).

Southern Appalachian Precipitation Patterns and Study

The southern Appalachian Mountain (SAM) region in the southeastern United States is influenced by a wide variety of synoptic storm types which can distribute precipitation maxima as a function of wind direction (Perry 2006). In the warm season, events are typically short-lived and convective in nature, influenced by air masses advecting from the Gulf of Mexico and Atlantic Ocean under influence of the semi-permanent Bermuda High (Kelly et al. 2012). In contrast, the same study showed that cold-season events are characterized by synoptic-scale fronts and longer-duration events combined with upslope mesoscale influences in favorable upslope regions. A third major synoptic influence during the wintertime in the SAM is Cold Air Damming (CAD) (Bell & Bosart 1988), during which a surface high to the north advects low-level cold air to the east of the Blue Ridge, providing the antecedent environment for either freezing rain or rapid diabatic cooling and snowfall via the isentropic overrunning of a Gulf-originating low to the south.

Efforts to study the high spatial variability of SAM precipitation, particularly snowfall, are relatively recent. The Northwest Flow Snowfall (NWFS) collaboration group (Keighton et al. 2009) consists of experts from six National Weather Service offices and universities representing the states of North Carolina, Tennessee, and Virginia. While consisting of researchers inside and outside the field of mountain meteorology, the group's disciplinary focus remains on NWFS, a phenomenon characterized as low-level orographic snowfall in the wake of synoptic-scale subsidence (Perry 2006). These events often produce heavy snowfall in favorable upwind escarpments while leaving lee-side barriers and valleys relatively snow-free. The group has attributed multiple enhancing factors to snowfall under NWFS conditions, including the role of antecedent air trajectories from the Great Lakes (Holloway 2007), surface heat and moisture fluxes (Miller 2012), and cloud microphysical processes observed using a vertically pointing Micro Rain Radar (MRR) (Yuter & Houze 2003).

The Roan Mountain MOPRAM's Contribution to Study

To mitigate this lack of high-elevation climatological data in the Southern Appalachians, the MObile Precipitation Research And Monitoring station was installed near the summit of Roan High Knob (elevation ~1875 m asl) on 30 September 2012. This automated weather station is capable of collecting hourly surface temperature, relative humidity, solar radiation, and liquid precipitation data. Additionally, an acoustic snow depth sensor allows for hourly snow depth measurements in an automated fashion; snowfall accumulation can also be determined using hourly snow depth differentials. Despite being in a location favorable for some of the highest annual snowfall amounts in the region (Johnson 1987), the site is relatively accessible due to its position in a state park near a well-maintained road. A 4 km access road beyond the main thoroughfare can require a cross-country ski to reach the station itself. This accessibility allows the frequent comparison of manual snow depth and snow liquid equivalent (SLE) measurements with the automated data.

This thesis explores the data from the 2012-2013 snow season (October-May) at Roan Mountain in conjunction with other nearby sites such as Grandfather Mountain (~1609 m) by developing an in-depth, short-term snowfall climatology while exploring unique and potent storms such as the remnants of Hurricane Sandy (see appendices A and B). After manually classifying snowfall events, a variety of descriptive statistics were derived relevant to known forcing behind NWFS (e.g., lapse rates, wind speed and direction). As subsequent years are added to this station's climatology, a more robust analysis of high-elevation snowfall characteristics can be derived and used by the climatological, hydrological, and meteorological community.

Snowfall Event Characteristics from a High-Elevation Site in the Southern Appalachian Mountains, USA

Running Head: High Elevation Snowfall Characteristics

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Abstract

Accurate assessment of snowfall patterns in high elevation remote areas is essential to providing the necessary boundary conditions for climatological analyses. The Southern Appalachian Mountain (SAM) region of the eastern U.S. provides a unique study area due to its low latitude and proximity to the Gulf of Mexico and Atlantic Ocean. Major snowstorms, such as Hurricane Sandy in October 2012, can result in heavy snowfall of 100 cm or greater in favored upslope regions. These characteristics make the understanding of precipitation patterns especially important as deep snowpack is often exposed to heavy rainfall, cloud immersion, and high dew point temperatures, further exacerbating flooding threats. To contribute to this understanding, the MObile Precipitation Research And Monitoring (MOPRAM) station was deployed at Roan Mountain (1875 m asl.) on the Tennessee/North Carolina border in October 2012. MOPRAM has allowed for the analysis of high-elevation variables such as temperature, liquid precipitation, and snow depth at high temporal resolutions during the 2012-13 snow season. In this paper, observed snowfall event characteristics are analyzed and compared with those of other sites in the SAM. The 25 snow events were characterized by conditionally unstable upstream lapse rates, northwest winds, high-to-low elevation precipitation enhancement near a factor of three, and 364 mm of seasonal snow liquid equivalent on Roan Mountain. About 391 cm of snow fell at Roan during the 2012-2013 season when using nearby snow liquid ratios as estimators.

Key Words: Orographic snowfall, new snowfall properties, southern Appalachian Mountains

1. INTRODUCTION

Understanding snowfall patterns in mountainous terrain can be especially difficult for forecasters and climatologists due to complex interactions between physical barriers and a poorly sampled atmosphere. What sampling does exist suffers complications from instrumentation challenges, especially when measuring snowfall (Rasmussen et al. 2012). Because the spatial scale of mountain influences is often very fine—on the order of kilometers or less—current atmospheric models cannot easily resolve precipitation patterns for a wide variety of snowfall regimes. At the climatological level, understanding how these fine spatial patterns are reacting to globally changing climatic shifts is important for predicting the outcome of many valuable hydrological resources. While comprehensive studies of mountain meteorology such as the Mesoscale Alpine Programme (MAP) have made important research contributions (Medina et al. 2005), the atmospheric processes and patterns in mountainous areas remain poorly understood due to low population and often inaccessible locations when compared to valley, coastal, or plains regions (Barry 2008).

The Southern Appalachian Mountain (SAM) region serves as a unique test bed for the analysis of snowfall climatology due to a combination of factors, including frequent snowfall due to a variety of synoptic regimes such as Gulf and Atlantic lows (Perry et al. 2010). Additionally, this region is characterized by considerable topographic relief leading to high spatial variability of precipitation. The most extreme of these spatial gradients is associated with northwest flow snow (NWFS), which is often characterized by orographically-enhanced precipitation on northwest slopes in the wake of synoptic-scale subsidence behind a surface cold front (Perry 2006). With an elevation range between 183 and 2,037 m asl, the SAM region has the greatest topographic relief in the eastern United States. Key features of this domain include the southeast-facing Blue Ridge Escarpment in NC, the Great Smoky Mountains National Park (GSMNP) and Unaka Range on the borders of NC/TN, as well as the Black Mountains of NC, home to Mount Mitchell, the highest point east of the Mississippi River (2037 m asl). Annual average snowfall in the region can range from less than 10 cm in the southeast foothills to over 250 cm in high-elevation windward escarpment regions such as Mt. LeConte in the GSMNP (Perry & Konrad 2006).

While observation networks in the SAM such as the Cooperative Observer (COOP) and North Carolina Environment and Climate Observation Network (ECONet) have grown in recent years (Holder et al. 2006), automated representation of favorable upslope snowfall sites remains lacking. To address this lack of sites, the MObile Precipitation Research And Monitoring (MOPRAM) station was installed on Roan Mountain just south of the Tennessee border (elevation ~1875 m asl) on 30 September 2012. Roan Mountain was chosen for two primary reasons. First, the site's combination of elevation and exposure provides it with the likelihood that it is snowiest place in the SAM south of West Virginia. While over 100 meters lower than Mt. Mitchell (2037 m asl), the massif's exposure to prevailing flow direct from the Tennessee Valley along with exposure to southeast winds provide substantial impact from multiple storm tracks (Johnson 1987). Second, the site has no known climatological observations, let alone those of an automated nature. This station provides hourly observations of temperature, relative humidity, liquid precipitation, and snow depth.

In this paper, results are presented from the first year of MOPRAM data, exploring in detail known driving factors of snowfall in the Southern Appalachians such as lapse rates, wind direction, and antecedent air trajectories. In addition, two case studies are explored in greater detail—the remnants of Hurricane Sandy and a prolonged late-March snowstorm—in order to analyze the atmospheric processes and associated snowfall patterns involved with events having relatively high societal impacts. The research project was largely motivated by the pronounced mesoscale variability of snowfall and associated atmospheric processes that often result in heavy snowfall on the higher elevation windward slopes and only trace amounts at downwind locations.

The guiding research questions are:

1. What atmospheric variables most influence snowfall event characteristics at high elevation sites (e.g., liquid equivalent, snowfall, lapse rates)?
2. What synoptic patterns (e.g., Miller cyclones, Alberta clippers) produced the bulk of the snowfall and snow liquid equivalent during the winter of 2012-2013?
3. How do snowfall and snow depth on Roan Mountain compare with other high elevation COOP stations located above 1,800 m asl (e.g., Mt. LeConte, Mt. Mitchell)?

2. BACKGROUND

Mountain regions are characterized in part by pronounced variability of temperature, precipitation, wind, and other parameters over small spatial scales (Barry 2008). However, most weather stations are located in valley regions and the density of observations is generally low. In the U.S., the challenge of poor mountain observation density has to some extent been mitigated in recent years, with the development of volunteer networks such as the Community Collaborative Rain Hail and Snow Network (CoCoRaHS) (Doesken 2007, Cifelli et al. 2005) and the NWS COOP program, the growth of which has been overtaken by state-level climate programs such as the NC ECONet. This instrumentation suite has complemented the existing COOP and Automated Surface Observing System/Automated Weather Observing System (ASOS/AWOS) station network and compares quite well with the COOP temperature and precipitation observations (Holder et al. 2006). Where gaps still exist in datasets, model interpolation projects such as the Parameter-elevation Relationships on Independent Slopes Model (PRISM) (Daly et al. 2008) have used known relationships of orography and nearby stations to create continuous grids of approximate precipitation values. While precipitation typically increases with elevation up to a certain point, the degree to which this effect occurs can vary greatly by region, synoptic regime, and mountain feature (Basist et al. 1994).

Despite advances in mountain observation and density such as miniaturized equipment, solar panels and telemetry (Barry 2008), observing precipitation—especially snowfall—still remains a challenge. Factors such as the phase-change of snowfall (e.g., melting, sublimation) as well as the physical redistribution of accumulations by wind are strong hindrances to properly assessing accumulation amounts (Doesken & Leftler 2000).

Undercatch of precipitation gauges also remains a problem, as light ice crystals are wind-driven away from collection sites, creating substantial error in snow liquid equivalent amounts. Rasmussen et al. (2012) assessed various configurations of snow gauges with results suggesting that great improvement in measurement can be found with those gauges surrounded by alter shields and fences or surrounded by dense bushes or forest, though these are not always practical due to limited space and cost. Attempts to model and potentially correct for blowing and drifting snow have also been explored to better explain the redistribution of snow in open environments (Gauer 1998).

In addition to measuring liquid equivalent snowfall in situ, developments in remote sensing technology have allowed scientists to determine the size, shape, and intensity of frozen hydrometeors. Multisensor approaches (Wu & Kitzmiller 2012) use a combination of radar and ground observations to determine precipitation values, but are limited in mountainous areas where beam blocking and poor ground representation exists. Optical disdrometers (Löffler-Mang & Joss 2000) allow for automated particle detection with high cost-effectiveness, making high-density snowfall monitoring suites more practical. Case studies using disdrometers (e.g., Parsivel, Löffler-Mang & Blahak 2001) demonstrated that they have good agreement with conventional C-band Doppler radar when detecting homogenous snowfall.

Snow depth also can be measured by automatic acoustic methods (Campbell Scientific 2011). When adequate thermal-acoustic calibrations and site selection are in place, snow depth can be measured to an accuracy of approximately one centimeter. However, errors can be introduced as a function of snow density—low-density snow, as a poor reflector of sound, is more difficult to accurately assess than existing/compacted snowpack. Using derived snow totals, these sonic snow depth sensors can accurately measure new snowfall in some cases, especially when derived at high temporal resolutions and when settling and compaction are accounted for (Ryan et al. 2008).

Mountains are capable of altering atmospheric circulation at all scales of motion. Mechanisms for this modification include transferring angular momentum to the surface through drag and friction, blocking/deflection of airflow, and modification of energy fluxes through clouds and precipitation (Barry 2008). Terrain can alter the climate at the regional level by acting as a barrier for downstream precipitation development, making regions arid that would otherwise have humid climates (Manabe & Broccoli 1990). In contrast, heavy precipitation can occur in mountainous regions as sufficient vorticity advection and lift combines with sub-freezing lower tropospheric temperatures. This advection process is enhanced further by flow up a topographic barrier. Snow precipitation efficiency through vapor diffusion is maximized when temperatures of approximately -12 to -15 °C exist in the snow growth layer (Auer & White 1982). Continental-oceanic gradients (i.e., coastal regions) can further enhance the differential vorticity development through baroclinic instability leading to explosive cyclogenesis and heavy snowfall, particularly in the northeastern USA (Carlson 1998). Once a cyclone has developed, mountains are capable of redirecting or even retarding the growth of synoptic-scale fronts (Schumacher et al. 1996). Synoptic or mesoscale cold pools have been shown to mitigate downslope warming and therefore increase spillover of orographic precipitation events (Zangl 2005).

Kinematic and thermodynamic mesoscale factors such as terrain height, wind speed, and stability are important drivers of orographic snowfall processes. Regional studies such as the Mesoscale Alpine Programme (MAP) have made great contributions to understanding of the processes determining orographic precipitation distribution through the exploration of factors such as static stability and latent heating on precipitation totals (Rotunno and Houze 2007). Terrain height and orientation are key elements in the placement of snowfall maxima (Colle 2004, Hughes et al. 2009) as well as melting height (Minder et al. 2011). Crest-level temperature has been shown to be an excellent predictor of snow-to-liquid ratio (SLR) which can be applied at lower elevations within the event level (Alcott and Steenburgh 2010).

Orographic mesoscale kinematic effects also dictate the precipitation outcome over small spatial scales (Garvert et al. 2007) or modify upstream precipitation amounts (Kingsmill et al. 2008). In a case study of winter storms in the western USA, boundary layer turbulence independent from stable stratified flow has been shown to enhance vertical motions and precipitation amounts (Geerts et al. 2011). Gravity waves have been identified as a contributor to both upstream and downstream precipitation totals (Medina et al. 2005). A predictable linear relationship between the Froude number and precipitation rate has also been derived (Hughes et al. 2009), with the authors showing that the predictability of this relationship degrades as a function of increasing Froude numbers in their modeling studies. Moisture fluxes from upstream sources such as lakes can significantly contribute to snowfall totals (Steenburgh et al. 2000). For example, parcel trajectory analyses have explored the origins of heavy snowfall in the southern Appalachian Mountains and have revealed a Great Lakes connection (Perry et al. 2007).

Microscale development of snowfall is realized as ice particles begin to generate upwind of an orographic barrier, initially growing larger by vapor diffusion as they advect closer to the terrain; this process can be enhanced by the presence of aerosols to bring higher snowfall amounts (Borys et al. 2000). Additionally, low fall speeds of frozen hydrometeors allow them to be more effective scavengers of low-level moisture; orographic enhancement is higher for snow than rain (Dore et al. 1992). A simplified model for orographic enhancement by Choularton & Perry (1986) shows that for a small hill in the mid-latitudes, snow rates were increased by a factor of four, compared to rain increasing by a factor of about two, for low and high elevation sites (dz ~600m). Microphysical interactions are also driven by stability, where unstable and unblocked flow allows for processes such as rapid coalescence (graupel generation) in warm (cold) environments (Medina & Houze 2003). Remote sensing techniques such as vertical pointing micro rain radar (MRR) also have been used in connecting cloud microphysical processes with mesoscale features such as fall streaks (Yuter & Houze 2003). Using detailed *in situ* observations, comprehensive habit diagrams have been made using the relationship between habit and temperature as well as the degree of supersaturation (Bailey and Hallet 2009); typically little supersaturation leads to minimum ice crystal growth while maximum dendritic development happens between -10 and -20°C at high levels of ice supersaturation.

Snowfall in the SAM is driven by a variety of synoptic and mesoscale processes depending on slope exposed to the windward flow. Northwestern slopes (e.g., Great Smoky Mountains and Unaka Mountains) see a majority of their snowfall from northwest flow snow (NWFS) events, those described as the orographic enhancement of snowfall in association with low-level northwest (270 to 360 degrees) flow (Perry 2006). Eastern escarpments such as the Blue Ridge, however, see most of their snowfall from Gulf lows as well as Cold Air Damming (CAD) events, during which a surface ridge in the northeastern U.S. wedges cold air against the mountains and allows isentropic upglide in the eastern mountains and Piedmont of North Carolina and Virginia while maintaining sub-freezing wet bulb temperatures near the surface (Bell & Bosart 1988). The synoptic characteristics regarding storm track and spatial distribution of snowfall have been studied in greater detail (e.g., Perry 2006, Perry et al. 2010, Kelly et al. 2012) as well as modeled statistically using a multivariate regression approach which has shown that the bivariate predictors of windward exposure and elevation exceeded elevation alone as a predictor of snowfall (Perry & Konrad 2006).

Focus has been made on NWFS due to its high spatial variability, wide latitudinal distribution in the Appalachians, and potential to produce heavy snowfall amounts. Collaborations between NWS offices and select universities continue to address the problems with NWFS forecasting while contributing to a growing climatology of synoptic snowfall event types (Keighton et al. 2009). These collaborations have found that a variety of influences such as moisture fluxes from the Great Lakes (Holloway 2007), ground heat and moisture fluxes (Miller 2012), and parcel trajectory (Perry et al. 2007) impact snowfall totals.

3.0 DATA AND METHODS

3.1 Roan Mountain MOPRAM

To build a unique climatology for a high-elevation site favorable for snowfall, the MObile Precipitation Research And Monitoring (MOPRAM) station was installed on Roan Mountain just south of the Tennessee border (elevation ~1875 m asl) on 30 September 2012 (Table 1). The custom-built platform includes the OTT Pluvio^2 weighing precipitation gauge and associated alter wind shield, OTT Parsivel^2 disdrometer and present weather sensor, Campbell Scientific CR1000 datalogger, sonic snow depth sensor, soil moisture and soil temperature sensors, solar radiation sensor, temperature and relative humidity sensor, and photovoltaic power supply and battery. The MOPRAM station site is located in a clearing surrounded by red spruce (*Picea rubens* Sarg.) and Fraser fir (*Abies fraseri* Pursh) trees, providing an optimal site for minimizing wind effects on precipitation measurements and snow accumulation. Unfortunately, an increasingly low sun angle, frequent storms, and associated cloud cover and snow build up on the solar array led to the failure of the separate battery for the OTT Parsivel^2 after just two events in November 2012. However, the remaining sensors, including the Pluvio^2 weighing precipitation gauge and sonic snow depth sensor, continued to operate on a separate power supply. Therefore, for this study, the Pluvio^2 is relied upon to identify precipitation events.

3.2 Wind and Radar Data

In addition to the Roan Mountain MOPRAM site, a suite of instrumentation on nearby high elevation sites allowed for the acquisition of additional data for each snowfall event. For the purposes of synoptic–scale wind and echo height determination, the geographic displacement of these stations from the original MOPRAM (Fig. 1) is relatively small, allowing for a reasonable comparison of variables not available at the Roan Mountain study site. Wind data were collected from 10 m towers atop Poga Mountain (1140 m asl) and Grandfather Mountain (1609 m asl). A vertically pointing Micro Rain Radar (MRR) (Peters et. al 2002) was deployed at 1018 m asl on Poga Mountain (25 km NE of Roan) to further contribute to both precipitation type estimation via hydrometeor Doppler velocity (Yuter et al. 2008) and investigation of the vertical structure of snow events (Stark et al. 2013).

3.3 Trajectory Analyses

Using the HYSPLIT EDAS 40 km trajectory model, backward parcel trajectories were analyzed ending at Roan Mountain (1875 m asl). By integrating these trajectories back 72 hours, patterns were determined between the origins of moisture, with particular interest in trajectories featuring some level of antecedent Great Lakes influence. Using a previously delineated series of domains (Fig. 2, modified from Perry et al. 2007), the amount of time each event spent in the individual sub-domains during the previous 72 hours was calculated to validate the understanding that a Great Lakes moisture flux can enhance snowfall totals (Holloway 2007). An additional calculation (3.3) demanded that an antecedent parcel reside in both Great Lakes regions for at least six hours each (for a 12-hour total minimum Great Lakes influence).

3.4 Snowfall Event Categorization

The time-frame for the snow events was determined using a multi-parameter approach combining hourly observations of snow liquid equivalent (SLE) precipitation, temperature, snow depth, and echo top height/MRR Doppler velocities. The beginning of an event was determined by the first hour when solid precipitation greater than 0.25 mm was observed; the maturation hour was the hour of heaviest precipitation as measured by the

Pluvio^2, and ending at the last hour of recorded solid precipitation. An event remained active as long as measurable solid precipitation was reported during a 6-hr period; breaks over 6 hours resulted in the identification of separate snowfall events. Snowfall events required that non-zero liquid SLE be recorded with surface temperatures greater than 2° C. Additionally, a total event snow depth differential of greater than 1 cm as observed by the sonic snow depth sensor was required to count as a snowfall event (Fig. 3).

MRR data were also used to determine melting layer heights, therefore allowing the determination of precipitation type for mixed precipitation events as a number of sub-freezing precipitation hours resulted in zero snow depth change from the snow depth sensor. Consequently, sub-freezing precipitation hours showing no snow depth change were typically classified as freezing rain, though a manual case-by-case analysis using MRR data determined if snow was also possible. These mixed precipitation events that likely minimized snow depth differentials were rather common, necessitating the corroboration of other parameters. By using a combination of reflectivity and velocity, snowfall (rainfall) levels could be determined by identifying the level at which lower (higher) reflectivity and fall speeds existed.

3.5 Derivation of Snowfall Event Statistics

Upon identification of individual snowfall events, statistical characteristics were generated based on raw and derived data (e.g., temperature, SLE, snowfall, relative humidity). The synoptic-scale circulation associated with each snow event was classified according to a modified version (Perry et al. 2013) of the Perry et al. (2010) manual scheme developed for an analysis of snowfall events in the Great Smoky Mountain region of the southern Appalachian Mountains (Table 2). Lapse rates were derived using the height differential between an upstream station and Roan Mountain (Fig. 1) and analyzed at the event level to explore the degree of instability within each snowfall period. The chosen stations were those whose directions from Roan matched most closely the direction of recorded wind at the event maturation hour. Temperatures at event maturation were used to further investigate the low-level temperature profile just upwind of Roan Mountain. The orographic enhancement factor was also calculated as the ratio of Roan SLE to Poga event total SLE. In this calculation, identical weighing precipitation gauges (i.e., Pluvio^2) with single alter shields in relatively sheltered locations were used, increasing the confidence in the comparisons.

Precipitation type was considered and broken up into rain, snow, and freezing rain; also analyzed were the precipitation events and intensity according to time of day (1200 to 0000 UTC and 0000 to 1200 UTC, respectively) to determine whether snowfall bands become better organized during the overnight hours, as suggested by Miller (2012). The addition of freezing rain for the study site was warranted after a sufficient number of hours showed substantial sub-freezing precipitation accumulation with little to no snow depth differential reported by the acoustic snow depth sensor. The method for seasonal snowfall estimation incorporated known snow liquid ratios (SLRs) for concurrent events by generating the product sum of SLE reported at Roan and the reported SLR at Poga Mountain. In the case of an event yielding only rain and/or negligible snowfall at Poga Mountain, a "warm SLR" of 5:1 (e.g., 200 kg m^{-3}) was applied to the corresponding Roan Mountain total to provide a conservative estimate of the snowfall.

4. RESULTS

4.1 Summary Statistics

During the 2012-2013 snow season from 1 October 2012 to 31 May 2013, 25 snowfall events occurred at Roan and were suitable for further study due to storm total accumulation being greater than 1 cm. (Table 3). Event dates ranged from 28 October 2012 to 04 April 2013. Variance within the event hours was particularly high, with event durations ranging from 1 to 69 hours in length; those of higher length were attributed to prolonged northwest flow snowfall, with the longest duration belonging to Hurricane Sandy. Total event liquid equivalent precipitation was 364 mm with event minima of 2 mm and maxima of 79 mm, the latter being attributed to Sandy as well.

4.2 Wind Direction and Radar

Wind direction histograms sampling the 472 event hours showed a strong northwest tendency for nearby Poga Mountain and Grandfather Mountain sites (Fig. 4a), indicative of the post-frontal nature of many of the snow events witnessed during the 2012-2013 season. Seventy-one percent (336 event hours) of wind records at Poga during snowfall events were between 270 and 360 degrees, with a small second maximum of easterly winds. Grandfather Mountain saw a similar dominance in northwesterly winds, with wind directions between 270 and 360 degrees observed during 67% (319) of event hours. Exploring a connection between wind direction and precipitation intensity, the percentage of event hours categorized as light (< 1 mm hr^{-1}), moderate (1mm hr^{-1} $<$ liquid precip $<$ 3 mm hr^{-1}), and heavy ($>$3 mm hr^{-1}) precipitation followed the same directional trends, with a slight shift south and westward for the heaviest events (Fig. 4b).

Radar analysis of the events showed that the greatest reduction in echo top height on average was from maturation to ending of events. While high echo tops (>6000m) were observed for a quarter of event beginning hours (25%), this value dropped dramatically for maturation hours (8.7%) to zero percent for ending hours. By contrast, few event beginning hours (3%) saw echo tops less than 2500 meters, while over a third (36.8%) saw these shallow values by the event ending hour. For event freezing level heights on average, the greatest reduction in freezing heights was observed during the beginning to maturation transition (Table 4).

4.3 Trajectory Analyses

Antecedent air parcels resided inside the final trajectory region consisting of the Ohio River Valley south to the Gulf of Mexico (domain 4) for over half of all trajectory hours (Table 5). Additionally, domain 1 (southwest) held almost a quarter (25.9%) of antecedent parcel trajectory hours. A small amount of parcel residence occurred in the Great Lakes domains during the 2012-2013 season, with only ~5% of total event hours seen in these regions. When binning hours according to the Perry et al. (2007) classification scheme, it was noted that 3 events (12% of total) were influenced by antecedent trajectories with a Great Lakes influence (i.e., parcel residence times >6 hours in both Great Lakes domains). The longest residence time in the Great Lakes domains (31 hours) was attributed to a ten-hour precipitation event during mid-February 2013 where only 5 mm of liquid equivalent precipitation fell.

4.4 Statistics by Synoptic Event Class

Summary statistics delineated by synoptic event type show a dominance of Miller-type cyclones (Miller 1946) throughout the season contrasted with an absence of cutoff lows (Table 6). While the greatest number of events were classified as non-U (0 < Maturation WD < 250), the greatest contribution by hours and SLE was attributed to Miller-type events. While non-NWFS events contributed less than a third of events, they contributed the highest total of SLE (41%) and consisted primarily of Miller-type events. The large contribution of X-U events was attributed to the Sandy remnants, as only one other tropical cyclone (Hurricane Ginny, 1963) may have resulted in snowfall in the southern Appalachian Mountains. The lowest observed wind speeds by synoptic event class were during an non-NWFS Miller event, with a wind speed of less than 1 m s^{-1} recorded at both stations. However on average, Miller-type systems had the highest event end wind speeds with an average of 36 knots; the outlier occurred on 07 November 2012 when light winds at maturation hour could be associated with a secondary upper-level low to the west cancelling out any northerly flow from the main system.

4.5 Lapse Rates

Upstream lapse rates for the 2013-2013 snowfall season ranged from -0.1 to 9.0 C km^{-1}, with a seasonal event maturation average of 4.65 C km^{-1} (Fig. 5). Additionally, it is important to note that the lower troposphere for seven of the twenty-five events was conditionally unstable ($6 < \Gamma < 9.8$ C km^{-1}). This finding should be taken into consideration as the degree of instability can allow for discrete, cellular snow squalls to be embedded within the larger-scale NWFS (Miller 2012); this phenomenon was noticeable at times on the MRR profiles. Only one event saw an inverted lapse rate at its maturation hour, indicative of an inversion layer typically seen with a CAD scenario (Bell & Bosart 1988). Lapse rate findings are consistent with the synoptic cold air advection regime characterizing a majority of the snowfall hours. Agreement between the chosen upwind site and the average of all sites for the event series was particularly high (r = 0.82).

4.6 Orographic Enhancement

With the exception of a few outliers, the ratio of Roan Mountain to Poga liquid equivalent precipitation totals remained a factor of approximately three (mean 3.2, Fig. 7). Nine events were not categorized due to a lack of reported concurrent precipitation at both the Roan and Poga Mountain sites. With enhancement ranging from 0.95 to 3.75, no particular pattern was observed with respect to the higher/lower enhancement ratios when considering the synoptic classifications overall. One of the lowest values (1.13) was in association with the mid-January rain to snow event which was classified as a non-NWFS Miller A/B; these low ratios can be attributed to the widespread, deep nature of the moisture layer evenly distributing precipitation. Conversely, the highest ratio (3.75) was in association with a mid-February cold front whose parent low (classified as an NE-U) was well to the north of the SAM. As is typical with NWFS events, the spatial distribution of precipitation was very limited, leading to the high difference in SLE between Roan and Poga despite their proximity to each other.

4.7 Precipitation Distribution by Type

During the cold season (October-May), nearly half (49.5%) of all precipitation hours were classified as rain (Table 7); about a third of precipitation hours (33.2%) were in the form of snowfall, with the remainder (17.3%) falling as freezing rain. The active months of the season (January, February, March) had a similar distribution of precipitation type, though as expected frozen precipitation increased at the expense of liquid, yielding a nearly even 3-way split in contribution among the precipitation types. Additionally, no substantial difference between daytime and nighttime snowfall amounts was noticed, each contributing to about half of the season's liquid equivalent precipitation total. Table 8 shows manual snow depth and density characteristics from a series of seven field visits throughout the season, highlighting the relatively consistent density of the snowpack (~200-300 kg/m^3).

4.8 Seasonal Snowfall Trends

Seasonal snowfall during the 2012-2013 season was estimated at 391 cm, somewhat higher than the observations of several windward high-elevation sites such as Mt. Mitchell (284 cm) and LeConte (327 cm, Table 9). While these values suggest seasonal snowfall slightly above the average annual snowfall for the most favored of windward escarpments (e.g., LeConte), it is important to consider that they are derived from local SLRs, introducing a level of error in the station comparisons. Seasonal trends in snow depth indicated nearly continuous snow cover from late December through early April. Roan Mountain saw considerably more snow depth and duration of snow cover than Mt. Mitchell (Fig. 7), further highlighting the importance of exposure alongside elevation when considering the location of snowfall maxima. Also of note were several easterly-flow events during which Mitchell snow depth exceeded that recorded at Roan. Additionally, snow depth greater than 1 cm (> 25 cm) was recorded during 51% (18%) of all hours on Roan Mountain between 01 October 2012 and 31 May 2013. The snowy start to the season was balanced by the relatively calm latter portion (April/May), during which no additional snow cover was observed at any station outside of the early April event. This translates to approximately 125 (43) snow cover days above 1 cm (25 cm). Additionally, snow cover was present 66% of the time during DJF and 88% of the time during JFM.

4.9 Case Studies

4.9.1 Hurricane Sandy

A late-October 2012 storm was a rare interaction of a potent upper-level disturbance with the remnants of Hurricane Sandy (Galarneau et al. 2013). In addition to disastrous flooding on the east coast of the US, the storm's cold sector left a potent amount of snowfall in the SAM region. This unusual snow event provided a unique case for the new instrumentation suite to record. In late October 2012 a long wave mid-latitude trough phased with a tropical cyclone (Sandy) undergoing extratropical transition (ET, Hart and Evans 2001) resulting in rapid cyclogenesis (Fig. 8) and strong prolonged northwest flow as the system passed to the northeast. The greatest values of liquid precipitation and snowfall of the season for Roan Mountain were also recorded (Fig. 9), while sustained winds at Grandfather exceeded 40 ms^{-1}

Precipitation from the remnants of Sandy began on 19 UTC 28 October as light rain that rapidly changed to snow concurrent with cold air advection. As the only event recorded by the Parsivel^2 sensor, the delineation of particular precipitation types by hour was possible; 61 and 8 hours of snow and non-precipitation hours respectively were recorded. By the event's end 31 October, 79.5 mm of liquid equivalent precipitation fell on Roan during the storm, the heaviest of which was at event maturation hour (3.3 mm hr^{-1}); this corresponds to 64 cm of snowfall using the 8:1 snowfall ratios manually recorded at nearby Poga. However, a site visit on 1 November 2012 measured 88 mm of SWE translating to 70 cm of snowfall, indicating about an 8% undercatch of the Pluvio. These values are comparable to the highest amounts reported by favorable upslope regions of the Appalachian Mountains. The storm was also characterized by high winds throughout the study region, though outside of some substantial high-elevation gusts the majority of the wind damage remained to the northeast; Grandfather Mountain saw peak wind gusts of 46.9 ms^{-1}, though rime ice accumulation on the anemometer may have limited it from recording even higher values.

Radar characteristics of Sandy were similar to other heavy NWFS events. High initial echo top heights (~4450 m asl) were moderately reduced to shallow levels (~2000 m asl) within hours of the beginning. Hurricane Sandy provided a unique case study due to the fact that all of the ingredients necessary for a potent NWFS event were in place for a majority of the event. Trajectory analyses from both event hourly precipitation maxima (22z 29 October, 11z 30 October, Fig. 10) indicate not only an Atlantic Ocean moisture flux at the mid-levels (~700 hPa), but also a secondary Great Lakes flux due to the cyclonic rotation that existed at the lowest to middle levels (below 700 hPa). Synoptic-scale ascent allowed for a deeper moisture layer to develop, especially in the central Appalachians near the storm center. An additional mesoscale-level enhancement of precipitation totals can be attributed to the high winds providing a strong orographic component to snowfall development.

4.9.2 Late March Prolonged NWFS

A second major snowstorm occurred in late March 2013 (Fig. 11), bringing in prolonged NWFS to the WNC region. A Miller B cyclone developed to the north and west of the study region on 25 March, with precipitation beginning shortly after midnight UTC; peak liquid precipitation rates shortly followed, exceeding 3.9 mm hr^{-1} at the event maturation hour (6 UTC 25 March, Fig. 12). The system slowly propagated northeastward, exposing the region to strong northwest winds, rapidly decreasing temperatures, and NWFS before the storm departed by the 27th of March, leaving 44.3 mm SLE (estimated 55 cm of snowfall) on Roan. HYSPLIT trajectory analyses at the two precipitation maxima for the event (2000 UTC 25 March, 1900 UTC 26 March, Fig. 13) display the contrast to Sandy's Atlantic moisture influence while also showing an element of Great Lakes fetch at the mid to upper pressure levels (~700-500 hPa). Radar trends were typical of a NWFS event. After an initial series of high echo tops (~4400 m asl), synoptic-scale subsidence quickly set in, keeping tops around 2300 m asl outside of a short period of heavier snowfall which brought tops 3000 m, possibly caused by a deepening of the planetary boundary layer at the maximum of daytime heating (Miller 2012).

This snowfall event (classified as a Miller A/B) had far less substantial snowfall totals than Sandy due to the absence of unique synoptic scale forcing and antecedent air trajectories originating from the Atlantic Ocean. The storm also featured westerly-originating trajectories, compared to those with maritime from the north and east observed in Sandy's remnants. Additionally, the echo top heights and intensity were lower for this system as observed by the nearby MRR (<2200 m asl) due to the lack of substantial synoptic influence, especially during the latter portion of the storm. The contrast between these two events serves as an excellent example of the variety of synoptic influences in the SAM region.

5. DISCUSSION

5.1 Wind Direction

Wind directions at Roan Mountain and nearby sites were characterized by dominance (>70%) in northwest winds during snow events, which compares well with the 88% from previous studies that have broken down this parameter (Perry et al. 2013). When looking at NW flow from event maturation hour alone, the 2012-2013 climatology had fewer events characterized than the average (16, 64%). Also present was a second but smaller maximum in easterly winds throughout the snowfall season. This bias in northwest winds agrees with the finding that a disproportionate amount of storms originated from either north or east of the study site with precipitation being associated with post-cold frontal flow; only 3% of snowfall on Roan was from GU-class events. Twenty-four percent of seasonal snowfall at Roan came from events classified as non-NWFS at maturation, however, suggesting that perhaps the transition to northwest flow occurred after the event maturation hour. While favored upslope towns such as Boone saw up to 81% of their average annual snowfall (34.6 cm), valley locations not commonly affected by NWFS saw totals well below the annual average; for example, Asheville received only 1 cm (8%) during the 2012-2013 season compared to an average annual snowfall of 30 cm. This lack of snowfall demonstrates the high spatial variability of these types of events in addition to the importance of easterly or southerly flow for precipitation in areas of the SAM not heavily influenced by northwest flow snowfall. Regardless of location, the influence of elevation and exposure to climatologically average wind directions is essential to providing the annual snowfalls observed in this highly variable spatial domain (Perry & Konrad 2006). As a major component of orographic precipitation processes, the knowledge of wind direction characteristics and climatology allows the identification of the most likely placement of precipitation maxima not only for the SAM, but also for other mountain regions (Basist et al. 1994).

5.2 Radar

Radar characteristics of snowfall events closely matched the distribution for a dataset collected from 2006-2009 (Perry et al. 2013); a majority of events were characterized by echo top heights between 2 and 3.5 km asl at the event maturation hour during the 2012-2013 season. On average, events had higher echo tops and melting heights at the beginning, with these heights decreasing through the event maturation and ending. The greatest change in melting height occurred from the beginning to the maturation of each event, suggesting that the most substantial cold air advection in the lower troposphere occurs before an event can mature. However, a reduction in echo-top height occurred most substantially between event maturation and ending on average, suggesting that the characteristic low-level flow associated with NWFS events does not develop until after a bulk of the liquid precipitation amount has fallen. This echo-top height decrease is likely caused by synoptic scale subsidence coincident with a capping inversion overtaking the area (Keighton et al. 2009). Approximately 16 (81%) of events were characterized by mostly continuous radar echoes while only two events (early November, late March) were characterized by a substantial portion of virga. Knowledge of radar echo top heights and intensity can be used to empirically determine snowfall intensity, and can be added as a corroborative factor with which to compare acoustic snow depth measurements since compaction would not be an inhibiting factor (Wolfe & Snider 2012).

5.3 Lapse Rates

Lapse rates are important to consider for diagnosing and forecasting NWFS events as precipitation amounts can in part be driven by convective instability (Miller 2012). Observed lapse rates varied as a function of wind direction when considering upstream sites as the initial temperature value. Nine events showed conditionally unstable low-level lapse rates at event maturation when taking the average of surrounding temperature profiles. However, only six events were conditionally unstable when considering only upwind stations when calculating the event maturation lapse rate. Any inverted lapse rates were associated with easterly or southerly flow. This observation further indicates the likelihood of a CAD-style scenario being in place when these wind regimes are present (Bell & Bosart 1988). On average, events with higher lapse rates had similar amounts of liquid precipitation when compared with the remainder of the sample (14.3 mm v. 14.4 mm stable and conditionally unstable, respectively). This suggests that convective activity on average was not a dominant contributor to the observed snowfalls at the event scale, though embedded convection can cause greatly enhanced hourly snowfall rates (Miller 2012). It is also worth noting that all but one “U” event had conditionally unstable upstream lapse rates. The effects of high lapse rates on atmospheric instability and snowfall totals seen in this study could be compared to those of the Great Lakes, where convection embedded within snowstorms can yield high snowfall amounts (Niziol et al. 1995, Holloway 2007).

A lack of diurnal variation in precipitation distribution in the dataset is also worth noting. Previous work (Miller 2012) has suggested that daytime heating provides a complex contribution to snowfall by deepening the planetary boundary layer in such a way that snowfall totals could be minimized, but this effect may be negated by the increase in upstream water vapor by the latent heat flux. Given that the results suggest an even distribution of precipitation overall by day and night, it is possible that these mechanisms are well balanced by each other, making nighttime totals not particularly different than those under daytime solar forcing.

5.4 Orographic Enhancement

The orographic enhancement factor allowed for a new perspective to be gained on the variability of precipitation change with elevation. Findings on average were consistent with the orographic enhancement model proposed by Dore et al. (1992), though the magnitude of the observations for snowfall events was greater than those found in Scotland. This may be attributed to the surrounding subsidence common to synoptic regimes in the SAM which can starve lower elevations of moisture. Observed enhancement values were also not uniform. This lack in consistency may undermine the usefulness of traditional regression models (Daly et al. 2008) in the SAM, especially during mesoscale-driven events. While other studies (Perry and Konrad 2006) have refined these multivariate regression approaches for the SAM, error still remains in statistical approaches, justifying the need to understand precipitation-elevation ratios as a function of more than just elevation or exposure.

6. CONCLUSIONS

The installation of the MOPRAM station at a high-elevation site favorable for substantial snowfall has allowed the development and investigation of a unique climatological dataset. In addition to collecting automated hourly observations, the relative ease of access to the study site allowed for manual data collection (e.g., SLR, snow depth) at times throughout the winter season. The inclusion of an automated instrumentation suite of temperature, relative humidity, precipitation, and snow depth used in conjunction with wind data from nearby sites will greatly bolster any attempts to confirm or modify existing hypotheses about climatology in the SAM as well as general orographic snowfall processes, particularly those that have explored the effects of NWFS on echo top heights, orographic enhancement/snow liquid equivalent differences between favorable and downstream sites.

As the event database from this unique station grows, future climatological studies validating knowledge about orographic snowfall processes can continue; the addition of Roan Mountain to the existing suite of monitoring stations will bolster the sampling availability for future research. The SAM region lacks a high sample size of stations at the crest of mountains, especially those on favorable NWFS escarpments. In this study, known driving factors behind substantial SLE amounts in the SAM (e.g., wind speed and direction, upstream lapse rates, antecedent air parcel trajectories) were explored in greater detail. Valuable data such as the historic remains of hurricane Sandy can be used in future in-depth case studies. Additionally, dramatic natural disasters can be caused by the nearly continuous nature of the snow cover; the ability to quantify high amounts of snow cover further demonstrates the hazards possible when mixing heavy rain on existing snowpack.

Despite the uniqueness of this dataset, questions about the automated findings remain. This project has shown the value of such a database and the need for its collection to continue. However, manual observations should supplement the collection. Intensive Observation Periods (IOPs) should be considered to validate the automated sensor data and other manually collected parameters, especially snow depth and lapse rates. Installing a wind sensor on-site would prevent any regional error introduced by using distant sites. Considering synoptic event characteristic in comparison with other low-lying sites could determine which climatological parameters play substantial roles in different regions of the SAM. Future investigation should continue in order to better detect trends of the driving factors with respect to larger-scale circulations such as the El Nino Southern Oscillation and Arctic Oscillation. Results from future short- and long-term atmospheric studies using these high-elevation data can be applied not only by interests in the Southern Appalachians, but also by other scientists investigating the physical patterns influencing orographic precipitation. These findings can be transferred to mountain regions with similar topographic characteristics to improve the knowledge of orographic processes and improve the ability of forecasters to save lives and property.

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Table 1: Data sources for short-term snowfall climatology at Roan Mountain.

Variable(s)	Elevation or Location	Temporal Resolution	Source
Temperature and Relative Humidity	1,875 m	1-Min	Vaisala HMP45C Probe
Grandfather Mountain Wind Speed and Direction	1,609 m	1-Min	RM Young 05103 Alpine
Liquid Equivalent Precipitation	1,875 m	1-Min	Pluvio Weighing Gauge
SYNOP Present Weather Code*	1,875 m	1-Min	Parsivel Disdrometer
Radar reflectivity and Doppler Velocity	1,018 m	1-Min	Micro Rain Radar (MRR)
Surface Analyses	United States	3-hr	NOAA WPC
New Snowfall, Snow Liquid Equivalent, and Density	1,875 m	12-hr	Manual Observations
Gauge-Collected Total Precipitation	1,018 m	12-hr	Manual Observations

*Unavailable after 07 November 2012

Table 2: Synoptic Event Classifications. From Perry et al. 2013.

Class	Description
NE-U	Northeastward tracking low passes to the north of area
SE-U	Southeastward-tracking clipper that passes north or across the area
M-U	Miller A/B cyclones originating in the Gulf of Mexico
CL-U	Cutoff Low -- A 500 hPa cutoff low moves across region (often slow & sometimes quasi-stationary).
LC-U	Lee Cyclogenesis -- Surface lows develops to the lee of the Appalachian Mountains
U	Upslope -- W/NW upslope flow in the absence of synoptic-scale surface features
Non-U	Non-NW flow events
X-U	Unclassified -- Does not fit any of the synoptic classes
**-U*	Denotes upslope flow (250 to 360 degrees) at event maturation for any of the synoptic classes

Table 3: Summary statistics for 2012-2013 event categorizations at Roan Mountain.

N = 25	Duration (hr)	Snow Liquid Equivalent (mm)	Snowfall (cm)	Temperature (C)	Relative Humidity (%)
Total	472	359	391		
Average	19	14	16	-6.7	93.5
Min	1	2	1	-15.4	83.6
Max	69	79	80	2.4	100

Table 4. Summary statistics for MRR event echo top and melting heights.

	Echo Tops (m asl)			Melting Height (m asl)		
	Begin	Maturation	End	Begin	Maturation	End
Average	3433	3102	2166	1479	1376	1358
Max	5650	5650	4150	2950	2950	2950
Min	1450	1750	1450	Surface	Surface	Surface

Table 5. HYSPLIT 72-hour Antecedent air trajectory characteristics for snowfall events.

Class	% Events	No.	Description
1	20%	5	≥36 h in region 1, no GLC
2	8%	2	≥36 h in region 2, no GLC
3.1	8%	2	≥6 h in W Great Lakes
3.2	8%	2	≥6 h in E Great Lakes
3.3	4%	1	≥6 h in W and E Great Lakes
4	40%	10	≥36 h in region 4, no GLC, <36 h in either regions 1 or 2
5	12%	3	Remainder
		25	Total

Table 6: Snowfall event characteristics at Roan Mountain by synoptic class.

Synoptic Class	Percent of Events	Percent of Snowfall	Percent of SLE	Duration (hrs)	Snowfall (cm)	SLE (mm)
NE-U	8%	3%	5%	25	11	17
SE-U	12%	20%	16%	36	63	57
M-U	24%	39%	21%	145	116	74
CL-U	0%	0%	0%	0	0	0
LC-U	0%	0%	0%	0	0	0
U	12%	12%	2%	91	25	9
Non-U	32%	22%	41%	86	88	145
X-U	12%	3%	16%	89	88	57

Table 7: Distribution of seasonal precipitation by type and duration for Roan for 2012-2013 snow season.

	Total	**SLE**			**Freezing Rain**			**Rain**		
Time Period	Precip (mm)	Total (mm)	%	% Hours	Total (mm)	%	% Hours	Total (mm)	%	% Hours
October-May	1350	353	26%	33%	144	11%	17%	854	63%	50%
January-March	655	222	34%	38%	122	19%	26%	310	47%	35%
Oct-May Day	721	182	52%	53%	100	70%	52%	439	52%	49%
Oct-May Night	630	171	48%	47%	44	30%	47%	414	48%	51%
U-Only Day	135	135	54%	51%						
U-Only Night	117	117	46%	49%						

Table 8: Manual snow depth and snow water equivalent (SWE) measurements taken during 2012-2013 snow season on Roan Mountain.

Date	Snow Depth (cm)	Total SWE (mm)	Density (kg/m^3)
1 Nov 2012	43	88	203
1 Jan 2013	20	44	219
22 Jan 2013	18	34	193
10 Feb 2013	28	65	232
4 Mar 2013	41	99	244
10 Mar 2013	48	141	292
30 Mar 2013	33	66	200

Table 9. Seasonal snowfall characteristics for 2012-2013 season at select sites.

Stations:	**Roan**	**Beech**	**Mitchell**	**LeConte**	**Poga**
Snow (cm)	391 (est)	254	284	327	168
Snow Liquid Equivalent (mm)	353	318	102*	330*	159
Roan Snow Cover:	**> 1 cm**		**> 25 cm**		
Hours	2975	Hours		1043	
Percent	51%	Percent		18%	

*Missing Data

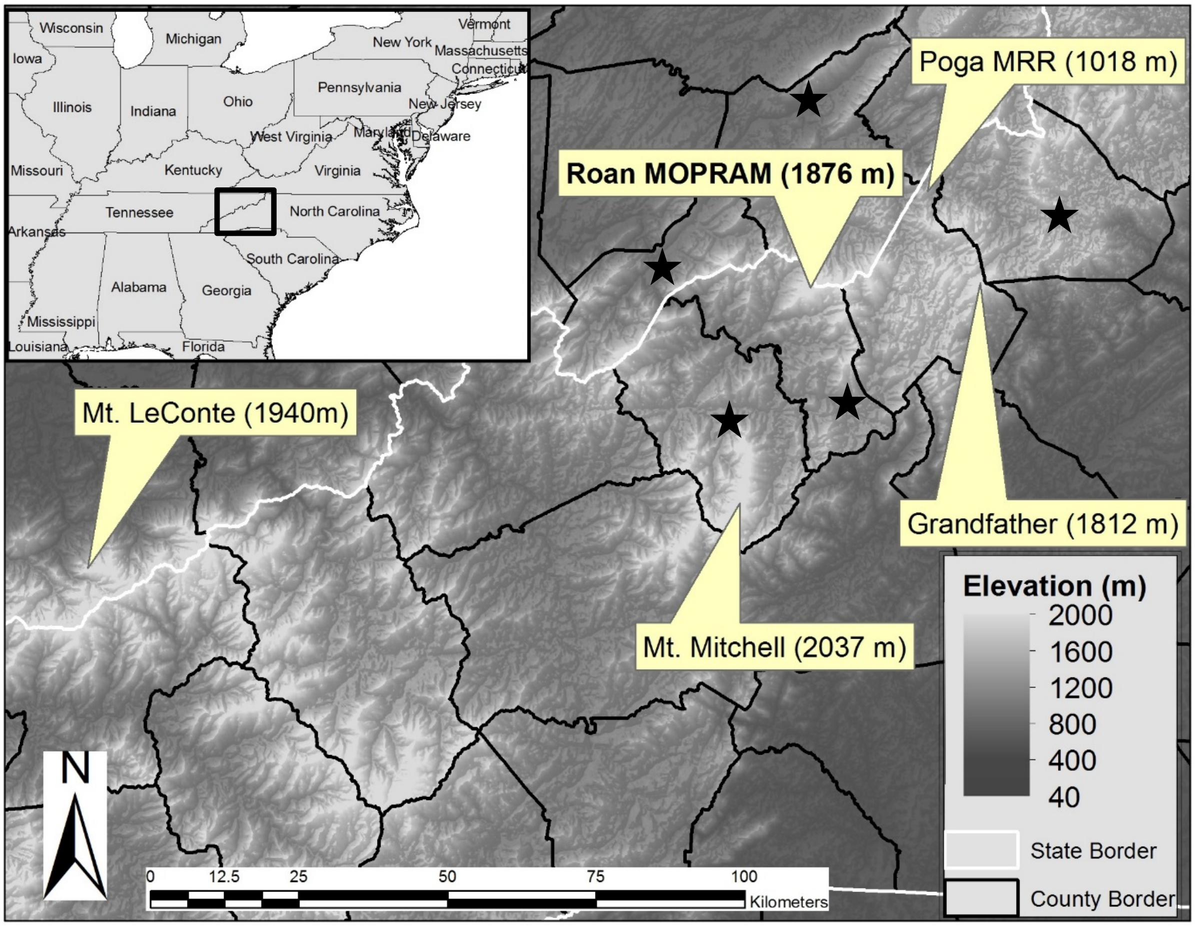

Fig. 1. Roan MOPRAM site with secondary monitoring stations. Upstream lapse rate locations starred.

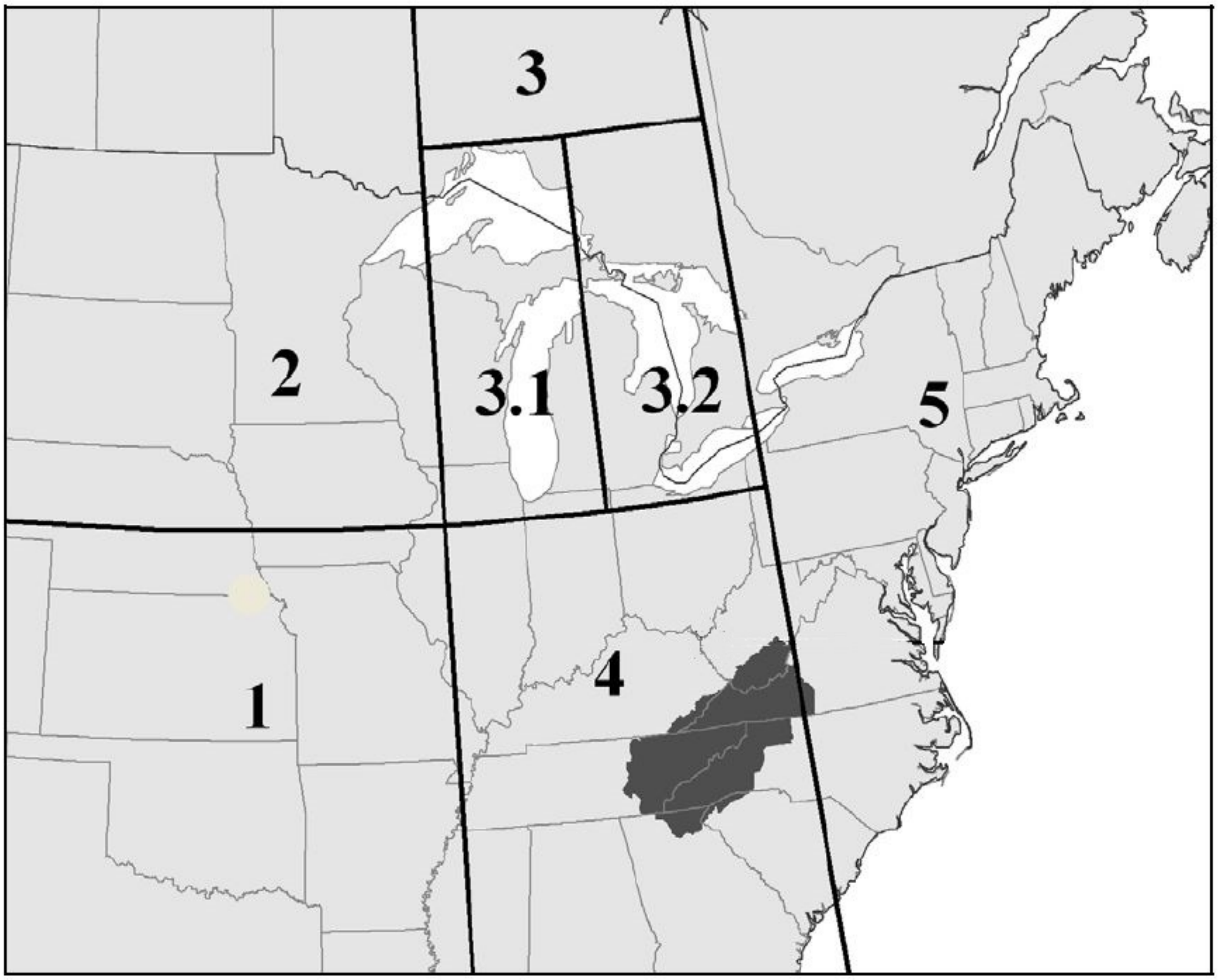

Fig. 2. Sub-domains for HYSPLIT backward trajectory analyses (SAM region shaded). From Perry et al. 2007.

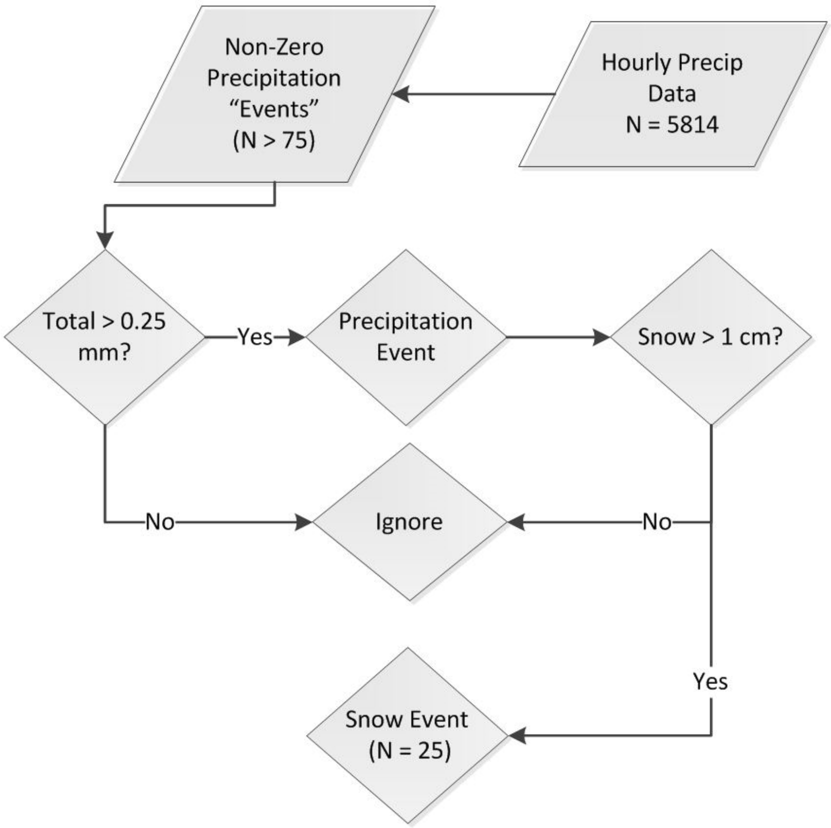

Fig. 3. Schematic for delineating snowfall events for 2012-2013 season at Roan Mountain, NC.

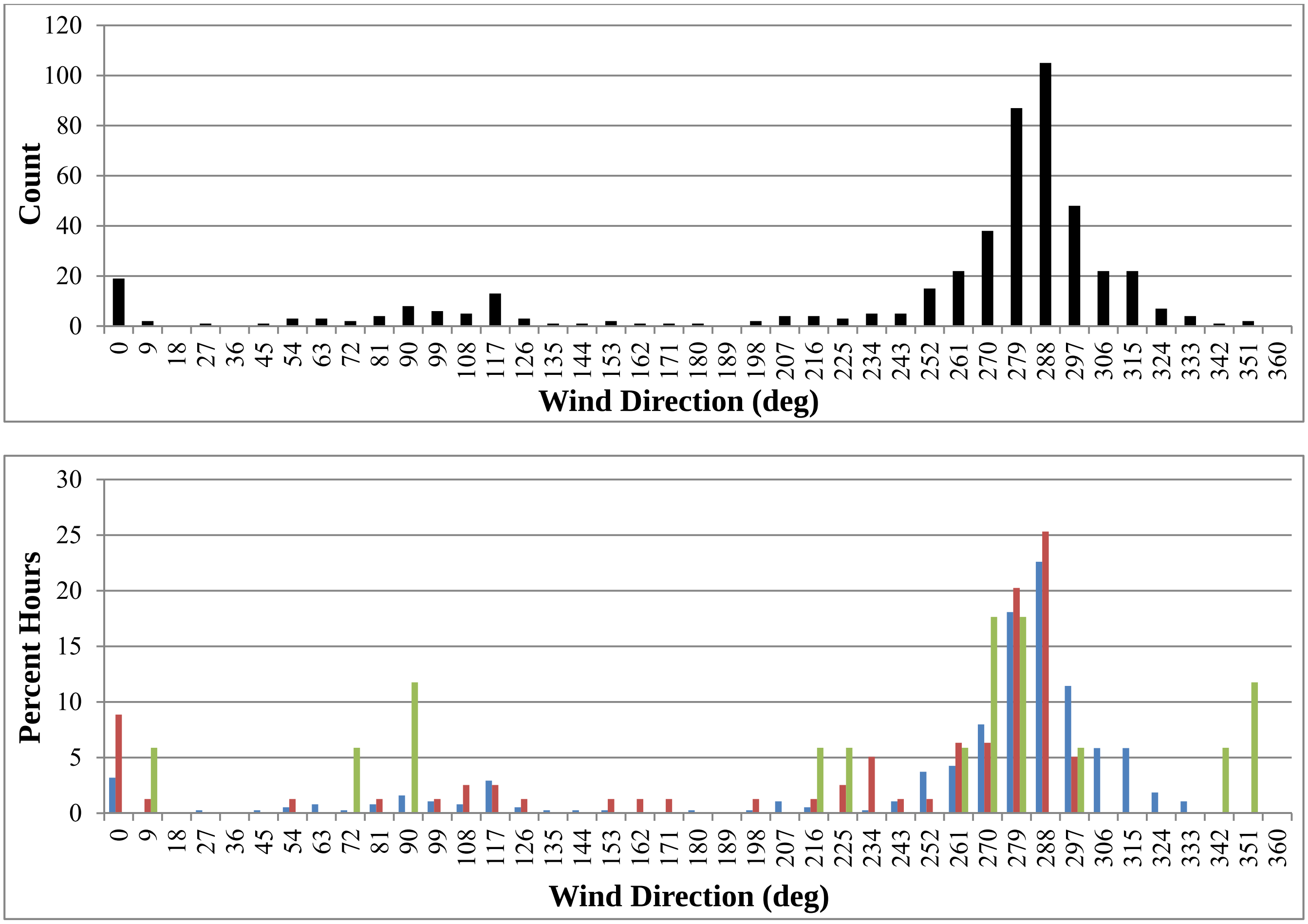

Fig. 4. Wind frequency histogram for all event hours at Poga Mountain (top), percentage hours by precipitation intensity (bottom: blue, light; red, moderate; green, heavy).

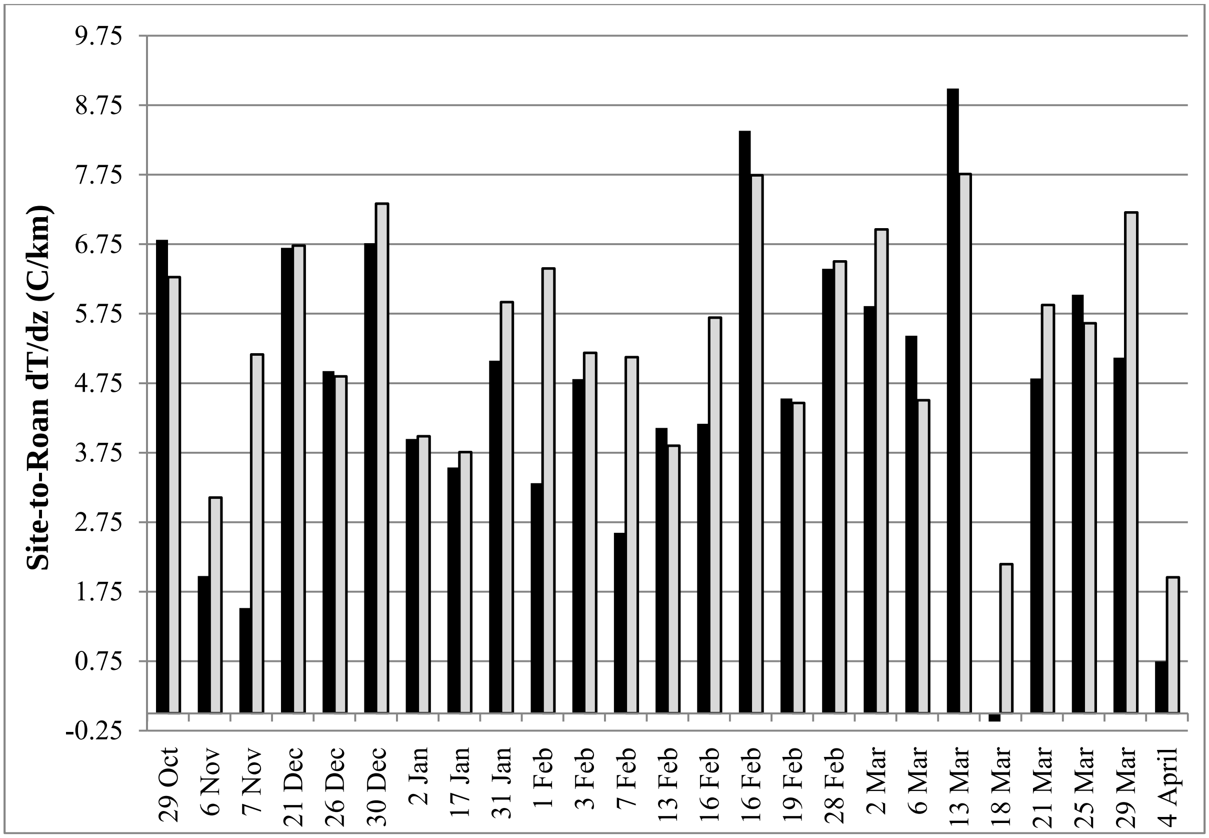

Fig. 5. Derived event maturation lapse rates by event number for upstream stations (black) and average of all stations (grey) for 2012-2013 snowfall season.

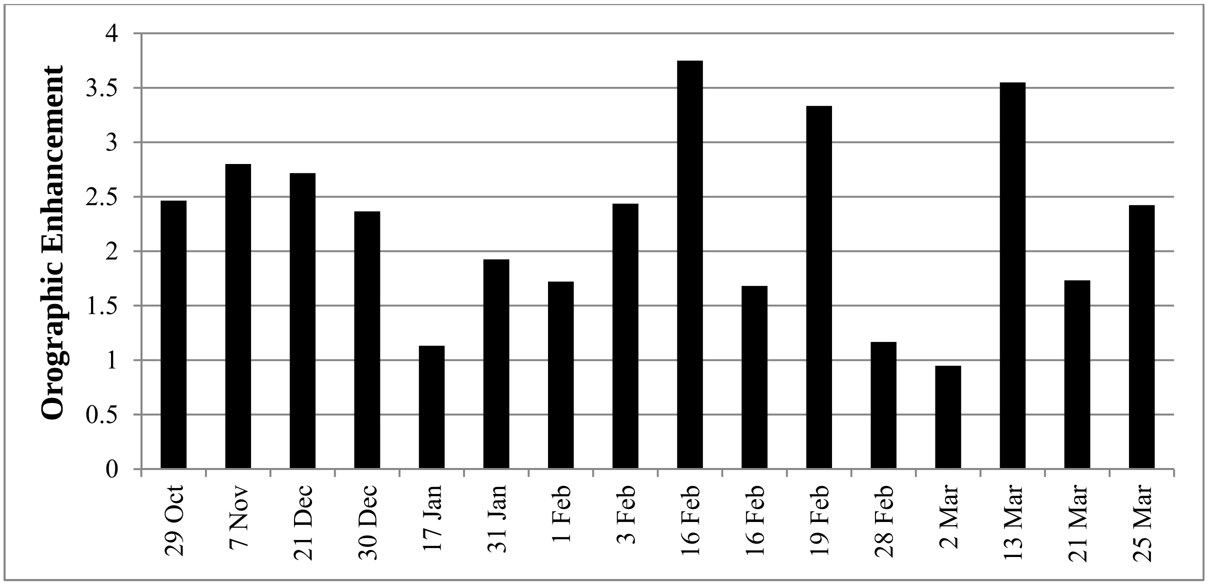

Fig. 6. Orographic enhancement ratios (ratio of Roan to Poga event total liquid precipitation) for snowfall events for season 2012-2013.

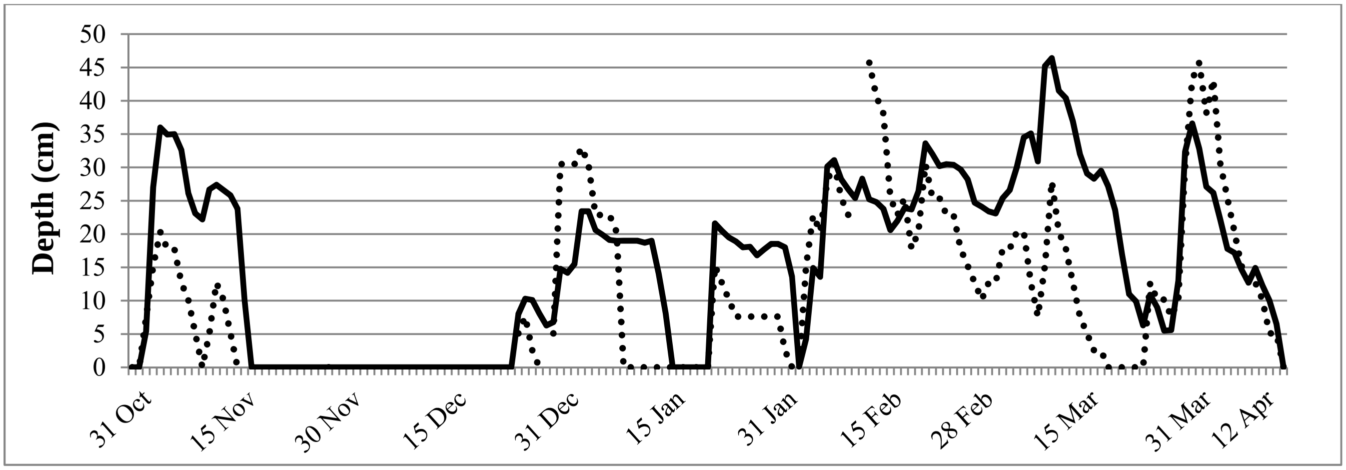

Fig. 7. Time series of snow depth from Roan (solid) and Mitchell (dotted) for 2012-2013 snowfall season.

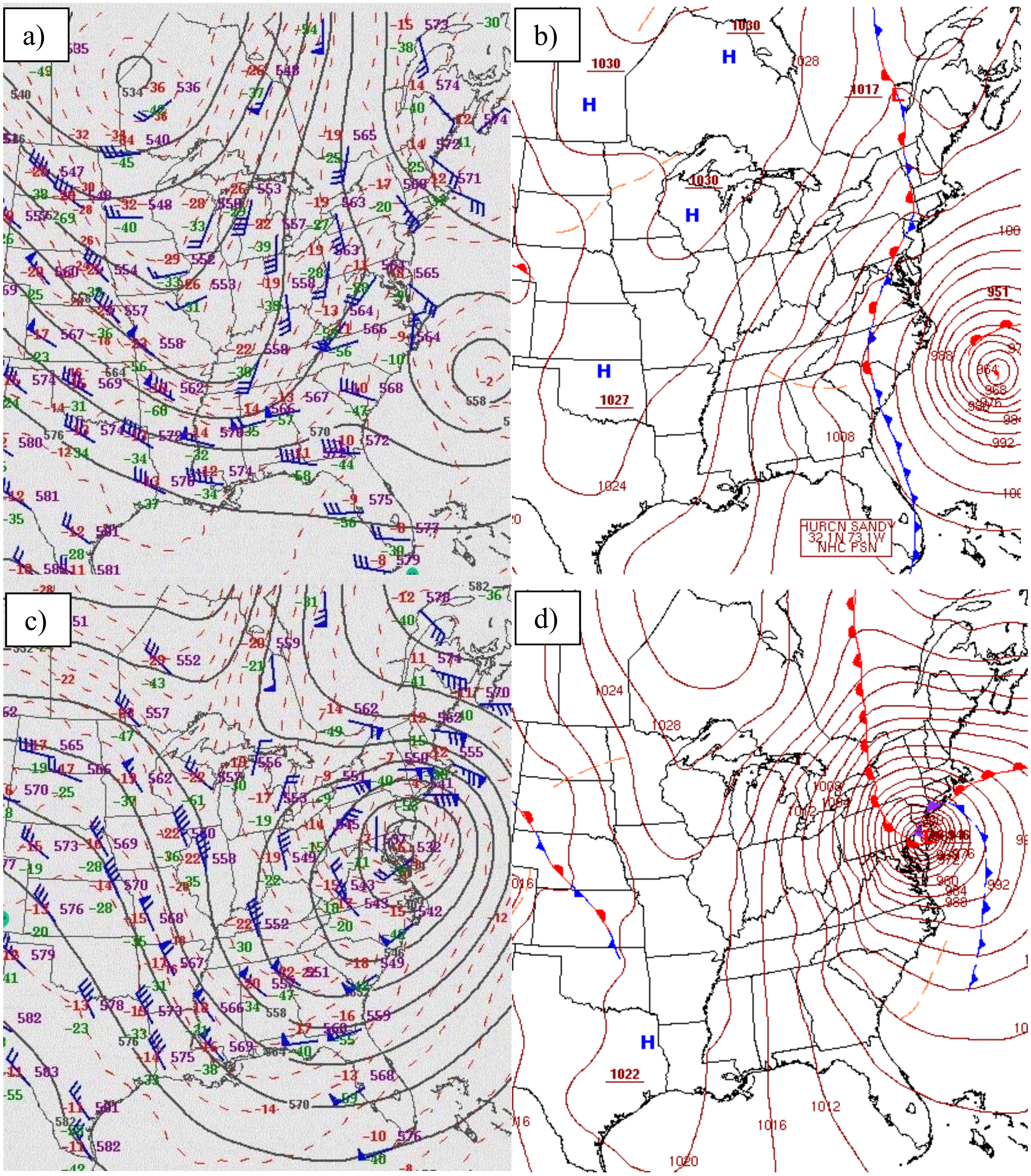

Fig. 8. 500 hPa heights, winds for 12z 28 October 2012 (a) and 00z 30 October (c), Surface analysis for same times (b, d).

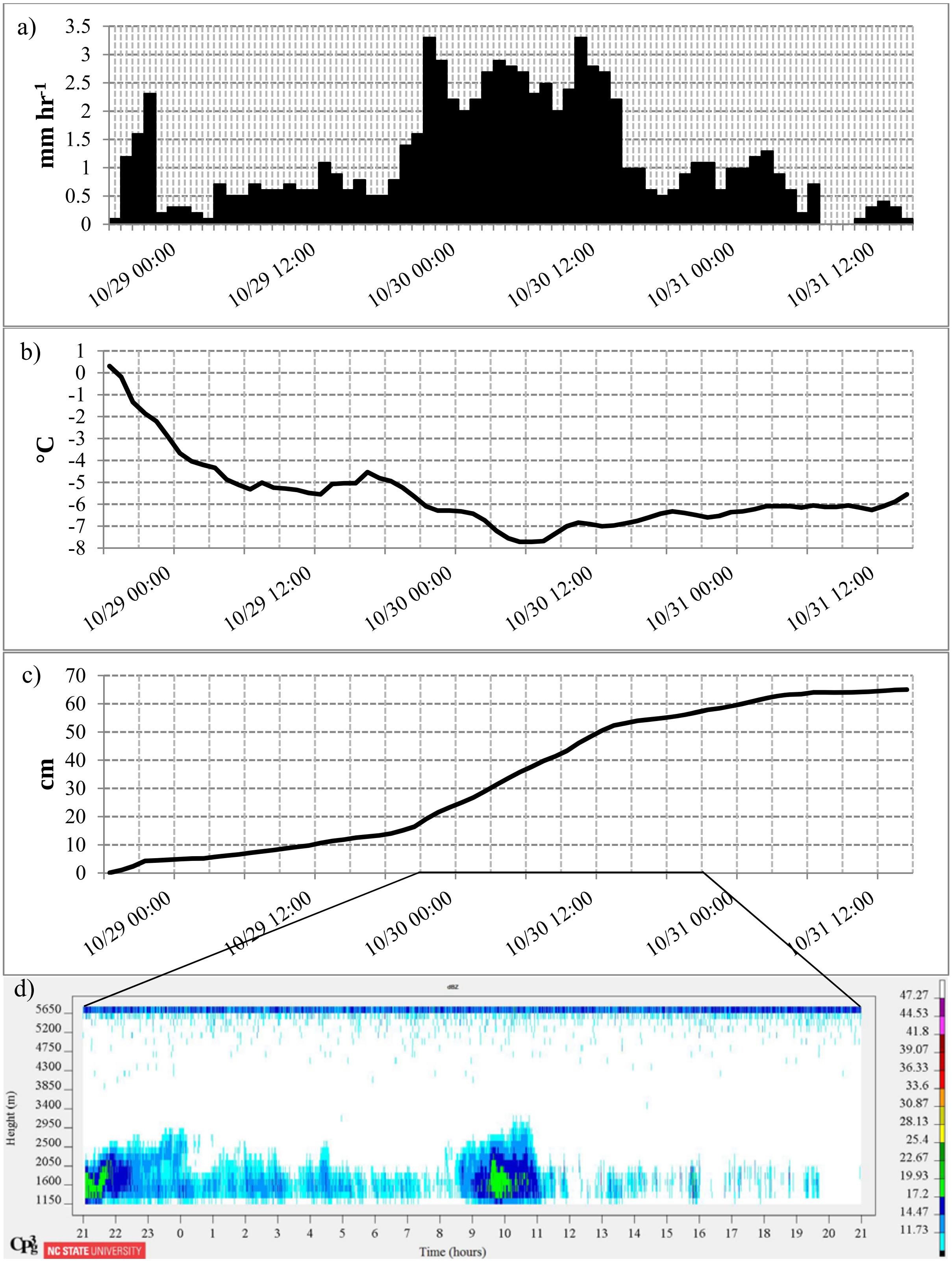

Fig. 9. Event duration hourly precipitation (a), temperature (b), cumulative snow depth (c), and radar reflectivity for 24 hour period ending 21 UTC 30 October (d) for remnants of hurricane Sandy (29 October-01 November 2012).

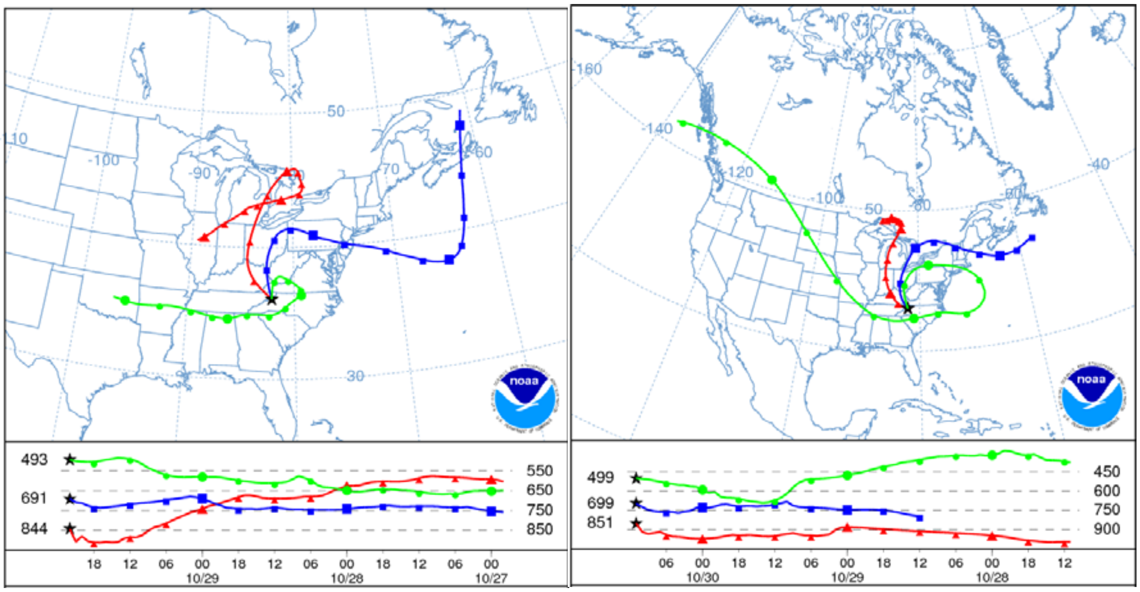

Fig. 10. 72-hr antecedent air parcel trajectory originating at event precipitation maxima (left: 22 UTC 29 October, right: 11 UTC 30 October) from snowfall episode associated with remnants of Sandy.

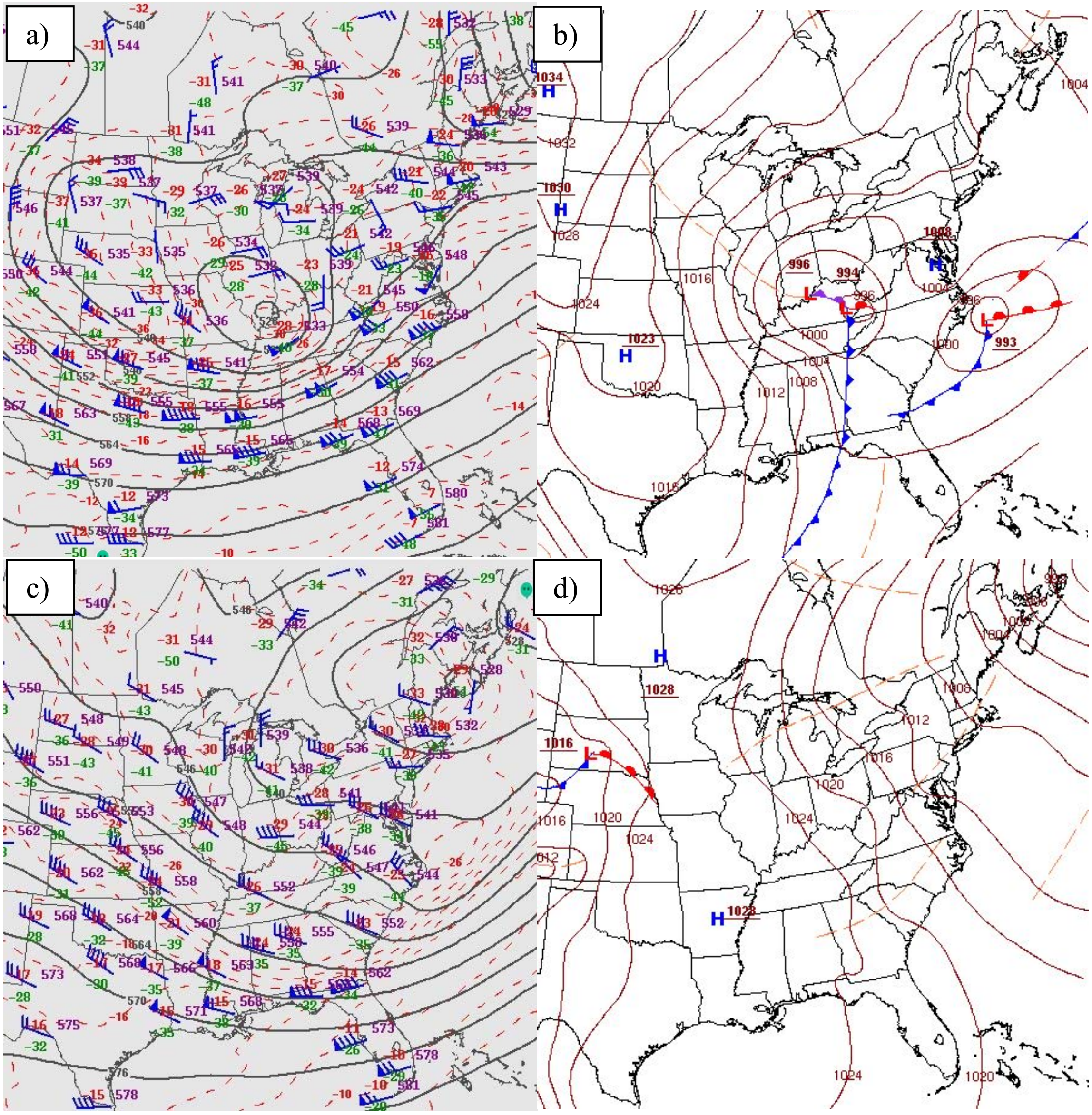

Fig. 11. 500 hPa heights, winds for 00 UTC 25 March 2013 (a) and 00 UTC 27 March (c), Surface analysis for same times (b, d).

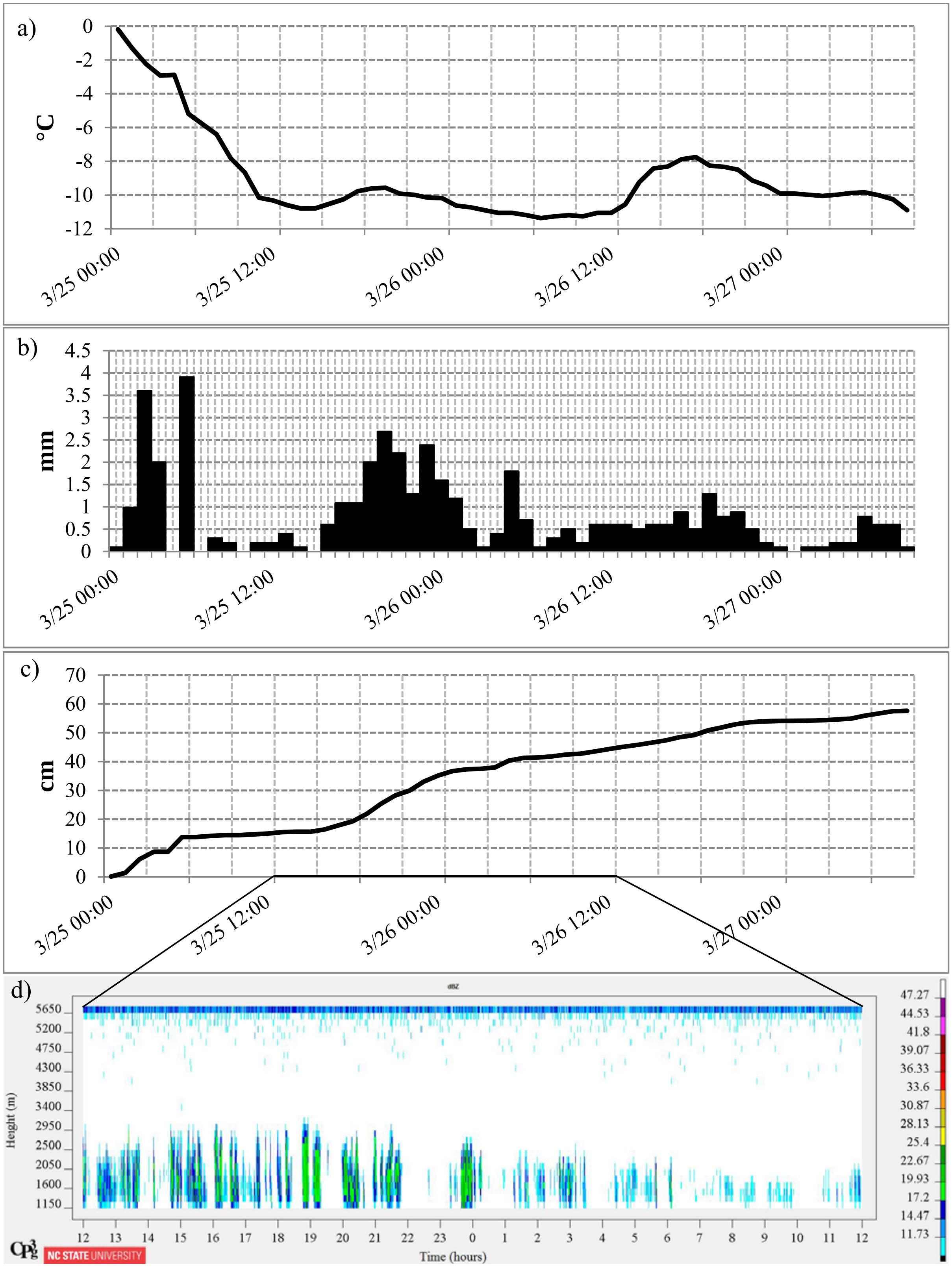

Fig. 12. Event duration hourly precipitation (a), temperature (b), cumulative snow depth (c), and radar reflectivity for 24 hour period ending 12 UTC 26 March (d) for late March snow event.

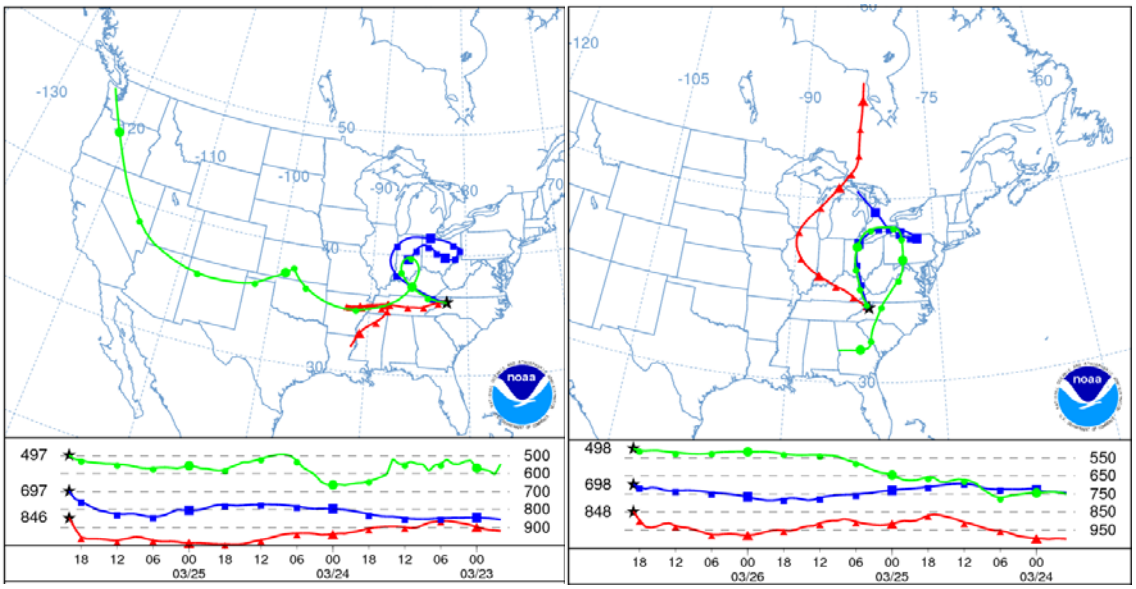

Fig. 13. 72-hr backward HYSPLIT trajectory plots for mid-March ending at event hourly precipitation maxima (left: 20 UTC 25 March, right: 19 UTC 26 March).

Conclusions, Limitations, and Future Work

Conclusions

Twenty-five snowfall events for the 2012-2013 snowfall season were manually categorized using automated data from the MOPRAM installed on Roan Mountain in September 2012. After developing an event database, each event was explored in greater detail with analysis focused on climate variables posited in past literature to have a substantial influence on Southern Appalachian snowfall patterns. Characteristics explored further included wind speed and direction, radar echo top heights and freezing heights, lapse rates, and orographic enhancement of precipitation. Special focus was also given to a case study on the remnants of Hurricane Sandy, an event that served as a potent synthesis of important contributing factors of snowfall. This event had some of the most extreme values (precipitation amount, duration) for the entire series of snowfall events.

A majority of events (~70%) were under the influence of westerly or northwesterly winds at the event maturation hour, with the average wind speed in excess of 7 ms^{-1} at Grandfather Mountain; peak wind gusts at the same site for the remnants of Sandy reaching 47.3 ms^{-1} at the same high-elevation site. Event maturation lapse rates suggested that atmospheric instability was not a major contributor of precipitation as only a few events were conditionally unstable. The greatest driver of snowfall remains at the mesoscale level, with orographic enhancement factors greater than threefold from Poga to Roan (1115 and 1875 m, respectively), suggesting that favorably located northwest flow sites can see greatly different snowfall totals as a function of altitude alone. Nearly half of all precipitation hours were in the form of rain during the cold season (October-May) at Roan, with over a quarter of liquid equivalent falling in the form of snowfall.

Limitations

The challenges of observing snowfall patterns in remote mountain environments remain a limitation to thorough collection of high-quality data. While automated methods suffice for certain variables such as temperature, relative humidity, and liquid precipitation, collecting automated snowfall measurements without manual intervention can produce misleading results. For example, during a manual snowfall report, it is convention to remove existing snowpack from a snow board immediately after taking a measurement which should limit any decrease in depth due to the compaction of denser snow below. In an automated environment, this compaction is accounted for by various algorithms (Jordan 1991), though as empirical derivations they can show numerical error as well.

Traditional instrumentation siting limitations existed in this test bed. A precipitation type sensor (Parsivel^2) allowed us to accurately determine precipitation type as a function of hydrometeor size and fall speed, but this device ceased function toward the end of the second event due to insufficient power from the solar panels. It is likely that as winter approached, a lowering maximum daily sun angle behind extensive tree cover lead to this power loss; the collection of nearby pine trees also limited daily insolation for the panels. In exchange, however, blowing and drifting snow was not a major issue thanks to this natural barrier combined with an on-site alter shield. In addition, wind and radar measurements were subject to spatial error as they were provided from stations well away from the main MOPRAM (~25 km away), though these distances sufficed for analyses of event characteristics at the synoptic level.

Future Work

The installation of the Roan Mountain MOPRAM site will allow for the detailed collection of meteorological and climatological data for a unique, high-elevation site for many years to come. In addition to the growing climatological database that can be used for climate experiments at multiple spatial and temporal scales, this site also can serve as a potent supplement for additional short-term mesoscale meteorological experiments and case studies.

Verification studies of automated measurements would greatly improve the communication and interpretation of results. Of special focus should be the verification of snow depth measurements. This item was already addressed to a degree during the first year as frequent data downloads and manual observations of snow depth were taken, but could be expanded via more extensive intensive observation periods (IOPs) during which hourly snow depth measurements could be taken to compare with those recorded by the acoustic snow depth sensor. Comparing derived lapse rates with balloon soundings during these IOPs would also be beneficial as a confidence interval with the report of derived results could be produced.

Field experiments could be complimented by model simulations and verification using *in situ* station data. Verification of regression models (PRISM, Daly et al. 2008) and reanalysis datasets (Kalnay 1996) as well as multisensor approaches to precipitation (Wu & Kitzmiller 2012) is important especially over mountainous terrain, where gridded datasets typically have the poorest representation. Understanding the degree to which these models show error and their particular biases will dramatically improve application of their output by climatologists and the forecasting community.

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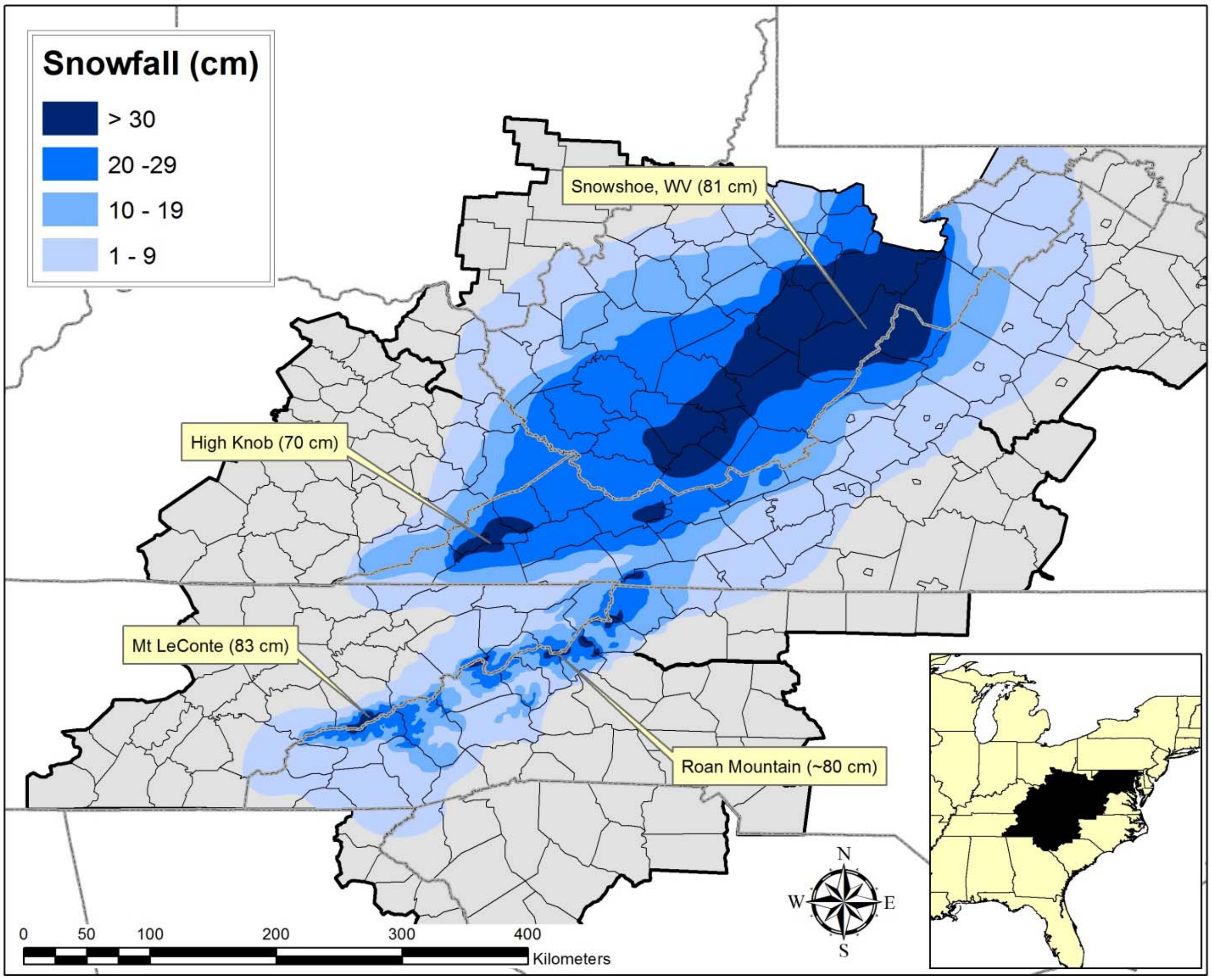
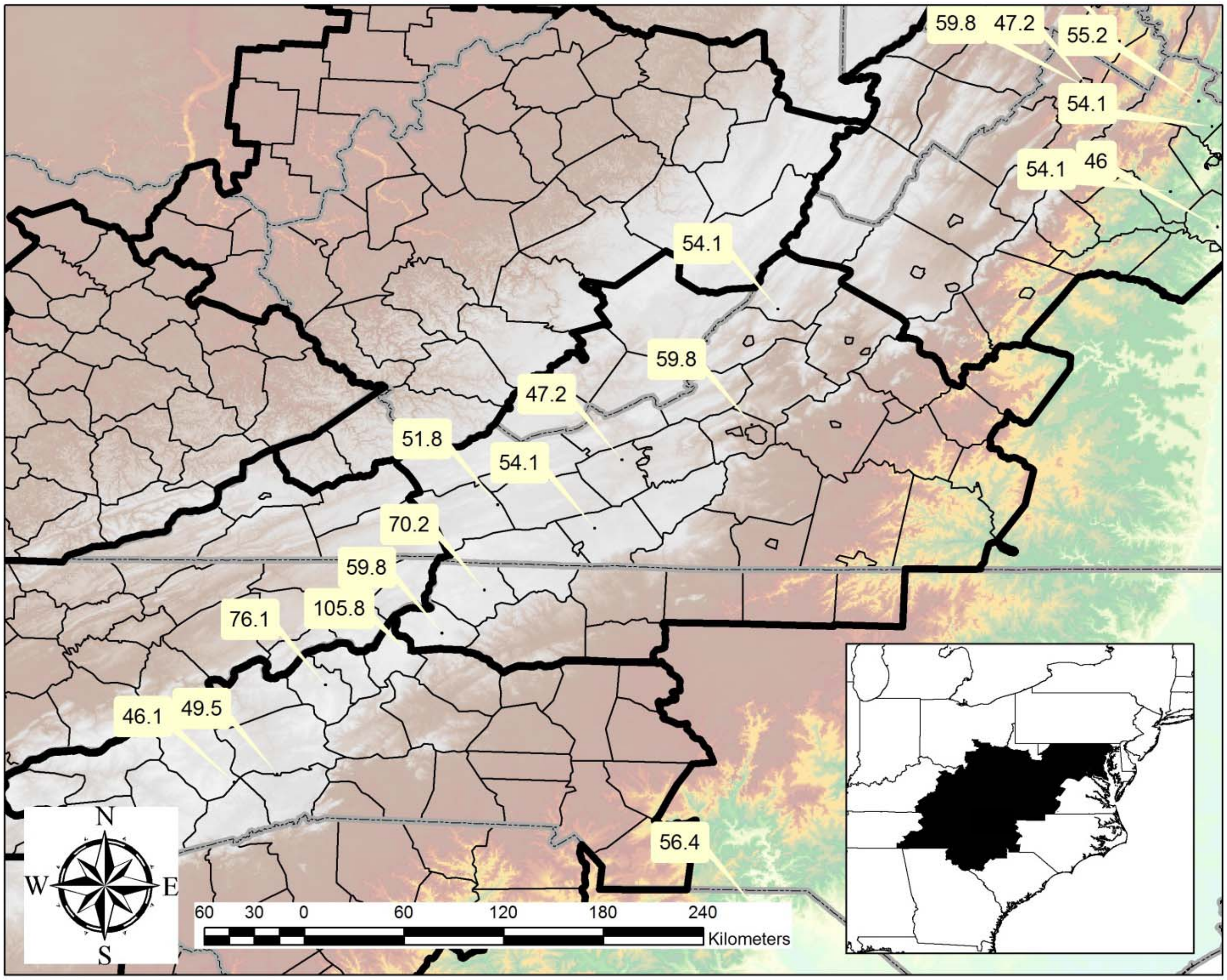
Appendix A:

Storm total estimated snowfall from Hurricane Sandy remnants, 29-31 October 2012



Appendix B:

Peak wind gusts (MPH) in SAM from Hurricane Sandy remnants, 29-31 October 2012



Vita

Daniel T. Martin was born in Galați, Romania in early 1989. Upon being brought to the USA by a pair of South Carolinian adoptive parents, his knack for curiosity and getting into trouble began. After moving to the Western North Carolina Mountains in 1999, he began to develop a sense of wonder and frustration at certain areas getting more snow than others; he was also not a fan of the simplified forecasts given by The Weather Channel, the NWS, or his local TV station. To explore this problem further, he pursued and successfully obtained a degree in the atmospheric sciences at UNC-Asheville, graduating in 2012. An aspiring teacher-to-be, his motivation to attend Appalachian State was driven by combination of a want for higher education which was supported by fellow Southern Appalachian snowfall enthusiasts; the town having some of the best weather in the Southeast may have also had something to do with it. This synthesis of circumstances allowed Martin to draft a thesis on a short-term climatology from a new automated station from one of the snowiest places in North Carolina. Uncertain at the moment what he will do next, he hopes it will revolve around studying precipitation and mountains—two of his greatest academic and recreational interests—in addition to remaining active as a member of the scientific outreach community.